REFERENCE BOOK

SIKORSKY HELICOPTER FLIGHT THEORY
FOR PILOTS AND MECHANICS

IN SUPPORT OF

THEORY OF FLIGHT

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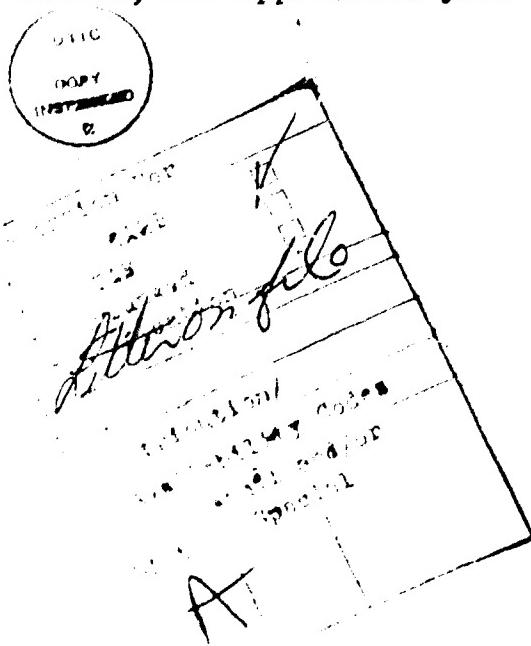
SIKORSKY HELICOPTER
FLIGHT THEORY
FOR
PILOTS AND MECHANICS

BY

JOHN R. MONTGOMERY

PREFACE

This text was written for use in the training programs of the Sikorsky Service School. Maintenance personnel, pilots, and the interested layman will find this material helpful in understanding the basic principles which apply to the fully articulated rotor system used in Sikorsky helicopters. It is not intended for the engineer or aerodynamicyst. Explanations given are simplified and are not in any sense offered as Sikorsky criteria, design or otherwise.

The author is indebted to Sikorsky Aircraft's Engineering Manager, Mr. Ralph Lightfoot, for knowledge imparted through the years and for his efforts in editing this publication for technical accuracy.

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June 1964

INTRODUCTION

In the days before the widespread use of the helicopter, it was relatively unimportant that the average aircraft mechanic possess a detailed knowledge of flight theory. While the technical education of maintenance personnel generally included a course on the subject, it was generally conceded to be information of the "nice to know" variety, but not mandatory for the successful performance of aircraft maintenance.

The advent of the helicopter produced, among other things, the necessity for the mechanic, as well as the pilot, to fully understand the aircraft being flown and maintained. For the pilot the requirement was definitely in the line of duty. The value of a knowledge of flight theory was recognized in the general helicopter maintenance field because of the following factors:

SUPPORT AND PROPULSION

While there are structural and aerodynamic relationships between the propulsion and support systems of the conventional, fixed-wing aircraft, the helicopter closes the gap completely. The propulsion system is also the support system and the complexities inherent in each are compounded because of the integration. To further emphasize the system interdependance, it need only be remembered that the propulsion-support system is also the means by which the control of the helicopter is accomplished.

TROUBLESHOOTING

Keeping in mind that the rotor blades of our propulsion-support system are hinged at their roots and have movement about three axes; that large, dynamic systems are subject to many vibrations, stresses, and moments; that the great centrifugal loadings involved will tend to magnify seemingly small errors in calibration, torques, adjustments, and other similar processes, it is reasonable to assume that adequate trouble-shooting would require more than a little knowledge of the systems involved.

AUTOMATIC FLIGHT CONTROL SYSTEMS

The introduction of automatic flight control systems to helicopters has certainly enhanced their utilization, especially in the area of all-weather flight. Because of the high degree of systems integration, personnel charged with the responsibility of maintaining the automatic flight control system must be thoroughly familiar with the helicopter's control, hydraulic, and electrical systems, as well as the circuitry of the electronic components. It follows that for a complete system understanding, a knowledge of helicopter flight theory is mandatory in order that the aerodynamic loops may be fully understood.

CONTENTS

Chapter 1

BASIC AERODYNAMICS

A working understanding of helicopter theory of flight must be predicated upon a basic knowledge of flight theory as it pertains to conventional, heavier-than-air craft. While the helicopter is capable of many maneuvers impossible to perform with conventional aircraft, and while a number of involved processes take place simultaneously during its flight, it flies for the same basic reason that any conventional, heavier-than-air craft flies, namely, air passing over its airfoils produces the aerodynamic force necessary to keep it aloft.

It is possible that many readers of this text have given aerodynamics little thought. There are some who have neither attended a formal course on the subject, nor felt any necessity for acquiring such knowledge. For this reason, the next few pages will be devoted to a review of some of the more important of the basic aerodynamic principles. It is felt that this review will assist those who have not studied aerodynamics or flight theory to better understand the sometimes complex discussions of rotary wing theory that will follow. For those readers who are knowledgeable in the field of aerodynamics, it is hoped that the review will not only serve as a refresher, but will present a means by which we may standardize our terminology.

The structure which makes flight possible is the *airfoil* — a surfaced body which responds to relative motion between itself and the air with a useful, dynamic reaction, *lift*. While we will continue to use the word to designate a lift or *thrust* producing structure, it might be noted that the term "airfoil" is more properly applied to the curvature or *camber* of the wing or blade.

Figure 1 illustrates a conventional, general purpose *airfoil section*. An airfoil section may be defined as the cross-section of any lifting or thrust-producing surface. As the diagram indicates, the thick end of the section
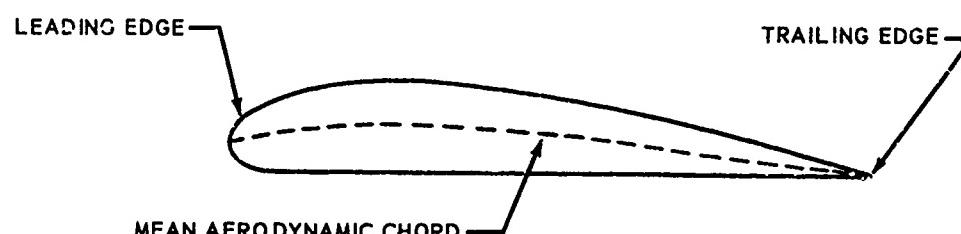

Figure 1 — Airfoil with camber.

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is known as the *leading edge*. The small, tapering end is the *trailing edge*. The distance between the leading edge and the trailing edge is known as the *chord* of the airfoil. If we consider that the curvature or *camber* of the upper and lower surfaces of the airfoil is, in all but symmetrical sections, not the same, it is apparent that a chord line passing midway between them would be curved. Figure 1 represents such a chord. It would be termed a "mean" or "average" aerodynamic chord. For the sake of simplicity, however, we will think of the chord as a straight line drawn between the furthermost point on the leading edge and the furthermost point on the trailing edge. Figure 2 illustrates such a chord on a *symmetrical* (double convex) airfoil section — the type used for most rotor blades today.
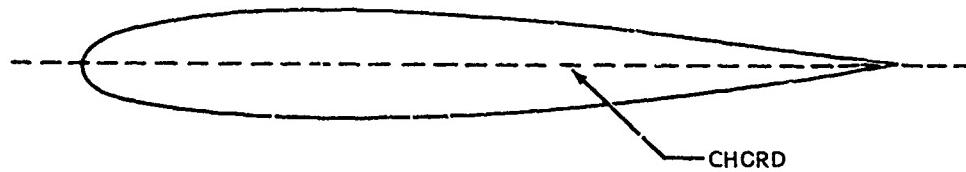

Figure 2 — Symmetrical airfoil.

When an airfoil is moved through the air, a stream of air flows over and under it. It is designed so that the flow will be smooth and will conform to the shape of the moving airfoil. If the airfoil is set at the proper angle and is made to move fast enough, the airflow will support the weight of the airfoil. This is the nature of the action that enables wings or blades to furnish enough lift to sustain the heavier-than-air craft in flight.

Before we discuss how lift is actually formed, let us examine the stream of air or airflow referred to in the preceding paragraph. First, let us eliminate what we normally term "wind" from our discussion. All future examples, illustrations, and discussions will assume a no-wind day. Logically, this means that any wind or airflow must be a *relative wind* — one created by the movement of an object through still air. Sitting in a motionless automobile on a no-wind day, we hold our hand out the window. We feel nothing. There is no airflow. Let us move forward at a speed of fifty miles per hour. We now feel air flowing over and under our hand. The speed of the airflow is fifty miles per hour. We have created a *relative wind* by moving our hand through the air. It flows opposite the flight direction of the object in motion. The velocity of its flow around or over the object in motion is the object's *airspeed*.
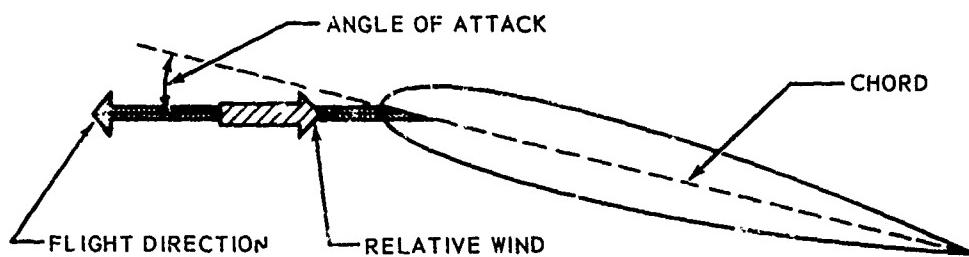
Figure 3 — Airfoil in motion.

In Figure 3 we see a symmetrical airfoil with its chord extended through the leading edge. We also see an arrow originating at a point on the chord line and extending through and beyond the leading edge. This arrow represents the direction in which we are going to move the airfoil through the ... As the airfoil moves through the air, a relative wind, indicated by the ... er, shaded arrow, will be created which will flow opposite the flight ... of the airfoil. The velocity of the relative wind will be in direct proportion ... the ... locity at which the airfoil is being moved through the air. *Relative ... velocity is airspeed.*

In Figure 3 we also notice that there is an angle formed between the chord of the airfoil and the relative wind. This angle is called the *angle of attack*. In fixed-wing aircraft the angle of attack follows simple rules when changing its magnitude. The angle of attack of a helicopter rotor blade can change due to a number of factors, some of which are controlled by the pilot and some of which occur automatically. There will be more on this subject later in the text.

When we consider the tremendous loads today's aircraft are capable of airlifting, the explanation of how a wing or a blade can be made to produce such large quantities of lift becomes an extremely interesting subject. We are now going to consider two explanations for the dynamic action produced by an airfoil flown at an angle to a relative wind.

As the airfoil moves through the air creating a relative wind, it is obvious that the wind is going to flow over and under it. The point at which the flow separates is called the *point of impact*. Here an air stagnation point or high pressure area is formed. Generally, at working angles of attack, the stagnation point is located at the lower portion of the leading edge thus contributing to lift. Immediately in front of the stagnation point the air separates, with the upper part of it forced to flow up over the top of the leading edge and the lower part of it flowing under the wing. Figure 4 shows the stagnation point or point of impact. It is marked with a small "x". The shaded arrow shows the direction of the relative wind and air flow lines are shown streaming over and under the airfoil section.
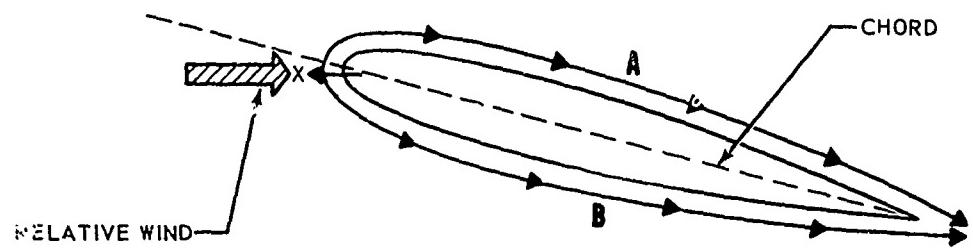
Figure 4 — Airflow around airfoil.

Notice that the airfoil is flying with a positive angle of attack and that the air leaves the trailing edge in a downward direction. The airfoil, due to the positive angle of attack, is *depressing or making the air go down.* In the case of the helicopter, this is called "downwash". In exerting this downward force to the air, the airfoil receives an upward counterforce. Remember Newton's Third Law of Motion which states, in effect, that "for every action there is an equal and opposite reaction." The lift or support the airfoil receives from deflecting the air downward can vary from zero to 100% of the total support required. On the other hand, if the airfoil is is nosed downward it may scoop the air upward causing a load *down* on the airfoil.

The lift created by an airfoil set at an angle in a relative wind may be explained in other ways. Let's consider the air flowing over the top of an airfoil. Look at the point of impact shown in Figure 4. If we measure the distance (A) from the point of impact to the trailing edge *over the top of the airfoil* and then measure the distance (B) from the point of impact to the trailing edge *under the airfoil*, we would find that the greater distance (A) is found over the top of the airfoil. The air traveling over the top is forced to travel a longer path and yet arrive behind the airfoil at about the same time as the air passing under to avoid a vacuum behind. To do so, the upper airflow must accelerate and in so doing experiences a reduction in pressure. The air passing underneath the airfoil decelerates. The pressure differential thus created results in an upward lifting force on the wing.

Why does the accelerating air moving over the top of an airfoil section experience a reduction in pressure? This was explained by Daniel Bernoulli. His Law or Theorum was developed for the flow of fluids through pipes. After trimming many technical and mathematical details down to size, we find that substantially the principle states that "the pressure of any fluid stream (air) is least where the velocity is greatest, and the pressure is greatest where the velocity is least". The Venturi tube, utilized in certain

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aircraft instruments and in the throats of carburetors, was designed to promote flow acceleration and its attendant pressure reduction. The tube is gradually reduced in diameter and then gradually enlarged to its original size. In the narrowest part of the tube the velocity of the air and/or fluid is greatest and the pressure is least. The shape of our airfoil sections was greatly influenced by the Venturi tube.
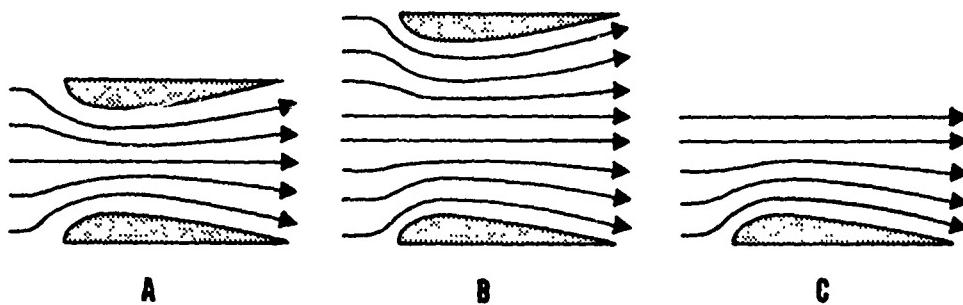

Figure 5 — Venturi flow.

In Figure 5 (A) we see a fluid flowing through a Venturi tube. The fluid streamlines are indicated by arrows. Notice that close to the walls of the tube the flow of the fluid conforms to the shape of the walls. At a point equidistant from the walls the streamlines are straight. In Figure 5 (B) we have pulled the walls of the Venturi tube further apart. We notice that the fluid streamlines close to the walls still follow the wall contours and that those further away from the wall tend to be less curved. Those in the center remain straight lines. Before entry into the Venturi tube the streamlines are equally spaced, indicating uniform flow velocity. Adjacent to the walls of the tube the streamlines come closer together, indicating that the velocity of the flow is greater at that point.

In Figure 5 (C) we have taken the upper wall of the Venturi tube completely away. We have left nothing but a curved surface with the flow lines immediately adjacent to the wall still following the contour closely and spaced closely together. It is thus indicated that the velocity of a fluid immediately adjacent to *a curved surface* will increase. The increase in velocity brings about a decrease in pressure. Notice the similarity between the remaining half of the Venturi tube in Figure 5 (C) and the shape of the upper surface of an airfoil!

Here is the very heart of the matter. If we can produce an area of sub-atmospheric pressure on the top of a wing, the greater pressure (atmospheric plus possibly some impact pressure) below the wing will create an upward force — *lift!* This pressure differential is quite small — in the neighborhood of one percent. Even this small difference, however, permits

adequate wing or blade loadings. Keeping in mind the fact that air has weight, mass, density — that it weighs about two pounds per cubic yard and exerts a sea level pressure of about 14 pounds per square inch, let us assume an atmospheric pressure of 14.70 pounds per square inch on the under surface of a wing. Airspeed and angle of attack combinations have produced a pressure of 14.49 pounds per square inch on the upper surface of the wing. There is thus a pressure differential of 0.21 pounds per square inch acting upward. This pressure is equal to 30.34 pounds per square foot — a wing loading which is quite reasonable for certain types of aircraft.

It was stated earlier that the lift required can be acquired from the downward deflection of the air produced by an airfoil being flown at a positive angle of attack. It is also true that the lift required can be supplied by the reduced pressure on top of a wing with only atmospheric pressure below the wing, i.e., no added impact pressure. These are two explanations for the creation of lift and cannot be added together. The latter case cited would be true for a typical, general purpose wing with its flat undersurface flying parallel to the relative wind. At this extremely low or zero angle of attack, or even at negative angles of attack, the low pressure on the top of the wing produced by its greater camber, creates the necessary pressure differential to supply the required lift. Naturally, as greater angles of attack are introduced and the flat underside of the wing meets the relative wind at positive angles, the greater impact pressure causes an upward reaction which adds to the lifting effort.

Four major forces act upon conventional aircraft. They are *lift, drag, thrust,* and *weight (gravity).* We have spent some time discussing how lift is formed. It is, of course, the force which, in general, counteracts gravity. *Drag* is the force which tends to retard or resist the motion of a body through the air. *Thrust* is the force which overcomes drag and propels the aircraft forward, or, as in the case of the helicopter, in any direction. *Gravity* (weight) is the force caused by the pull of the earth. At this time let us have a closer look at the forces we refer to as lift and drag. With regard to the expression "drag", we will limit our discussion for the moment to that drag which acts only upon the wing.

Lift and drag (wing) are components of the total aerodynamic force acting upon the wing. This total force is called the *resultant.* Each tiny portion of the wing in flight has a small force acting upon it. The force acting on one small portion of a wing is different in magnitude and direction from all of the other small forces acting upon all of the other portions of the wing. By considering the magnitude, direction, and location of each

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of these tiny forces, it is possible to add them all together into one resultant force. This resultant force has magnitude, direction, and location with respect to the wing. If we carry the resultant into the wing until it intersects the chord, the point thus derived is called the *center of pressure*. It can be said that lift acts from the center of pressure or, stated another way, the center of pressure is the center of lift.

Later on we will discuss the movement of the center of pressure with change in angle of attack and the implications of this movement with respect to our choice of an airfoil for rotor blades.

The resultant force on a wing flying at a specified speed and angle of attack might be discussed as a single entity possessing both magnitude and direction. Such a situation is shown in Figure 6.
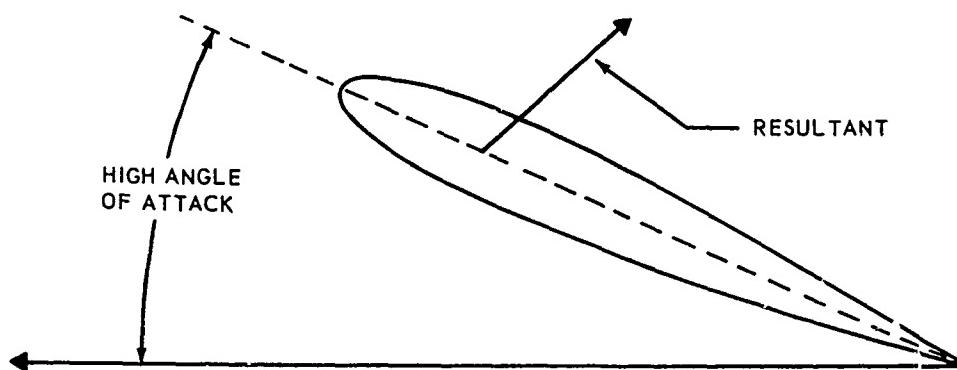

Figure 6 — Resultant force.

It is also possible to break the resultant down into two major components with magnitudes in two directions. In aerodynamics it is expedient to discuss these component forces as having directions perpendicular and parallel to the relative wind. The component of the resultant force which acts perpendicular to the relative wind is *lift!* The component of the resultant force which acts parallel to the relative wind is called *drag!* Figure 7 shows a wing with angle of attack, relative wind, and the resultant with its component forces, lift and drag. Naturally, changing either the angle of attack or the airspeed will cause changes in the direction, location, and magnitude of the resultant. Any change in the resultant will cause changes in the magnitude and direction of the component forces. Keep in mind that in describing lift and drag, no mention was made of horizontal or vertical directions. If the relative wind is horizontal, the lift is vertical and the drag is horizontal. If the relative wind is not horizontal, then the lift is not vertical and the drag is not horizontal.

Lift is a variable force. Many factors govern the amount of lift generated

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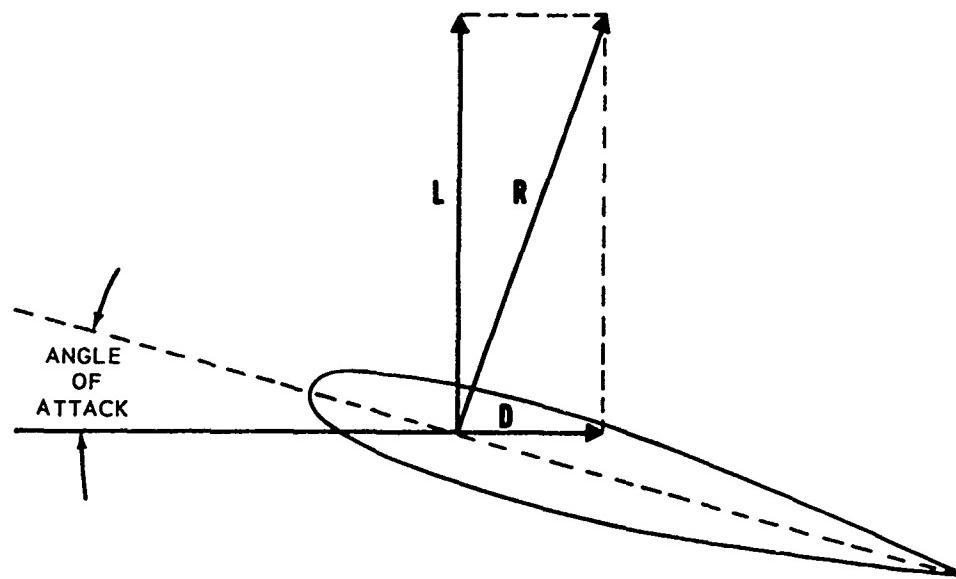
Figure 7 — Resolution of forces.

under stated conditions. For example, as speed increases, lift increases because the increased flow velocity over and under the airfoil causes a larger pressure differential. Lift does not vary in direct proportion to speed, however. Lift varies as the square of the speed. An aircraft traveling at 100 knots has four times the lift it would have at only 50 knots.

The density of the air influences lift. Lift varies directly with density. At 18,000 feet, where the density of air is just half that at sea level, an aircraft would have to weigh only half as much, or else travel at 1.414 (the square root of 2) times as fast as it would at sea level to maintain altitude. Remember that lift varies as the square of the speed. If some factor reduces the lift by half (the situation that exists at 18,000 feet) we have to increase the speed so that the square of the new velocity is twice the square of the original velocity.

From our previous discussions of how lift is produced, we have seen that the shape of the airfoil influences lift. Generally speaking, the greater the camber or curvature of the airfoil, the greater the lift.

Lift also varies with the area of the wing. A wing with an area of 200 square feet will lift twice as much at the same angle of attack and speed, as a wing with an area of only 100 square feet, providing proportion of wing and airfoil section are the same.

The angle of attack greatly influences lift. The greater the angle of attack, the greater the lift — this condition prevailing until the angle becomes so great that the flow of air over the top of the airfoil can no longer follow the camber smoothly, but is broken up and *burbles*. The wing

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is then partially or fully stalled depending on the severity of the angle and the aerodynamic characteristics of the airfoil.

Referring to Figure 7, the component of the resultant force which is parallel to the relative wind, drag, can be broken down into two basic types. These are *profile* and *induced*. They are peculiar to lift or thrust-producing airfoils. *Profile drag* is the frictional resistance incurred when an object is moved through a viscous fluid. Air may be considered such a fluid. In simple terms, it is "sticky" and tends to cling to an object passing through it. This fact would indicate that the cleaner or more polished the object is, the less profile drag incurred. *Induced drag* is the drag incurred in the production of lift. When an airfoil is flown at a positive angle of attack, air is forcibly made to move in directions, at velocities, and under pressures which are not normal to its free state. Its resistance to these changes which are necessary to produce lift, forms the type of drag we call *induced*. The remaining type of drag is termed *parasite*. Parasite drag is that which is incurred by any portion of the aircraft which does not contribute directly to lift or thrust. Cowlings, landing gear, struts, pitot tubes, fuselage, and other accessories are examples of parasite drag producing structures.

Drag will be further discussed in the section of this text devoted to power requirements.

In our discussion thus far, we have referred repeatedly to airfoils and airfoil sections. We have mentioned a general purpose airfoil with convex upper and flat undersurface. We have talked about a symmetrical airfoil. Figure 8 shows three basic types of airfoil sections.

Each of the three basic types shown possesses certain excellent characteristics. Each has certain drawbacks as well. Which would be the best

GENERAL PURPOSE

HIGH SPEED

HIGH LIFT
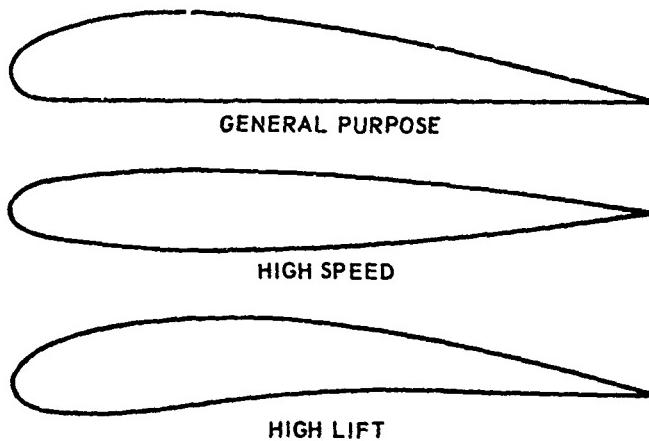
Figure 8 — Airfoil types.

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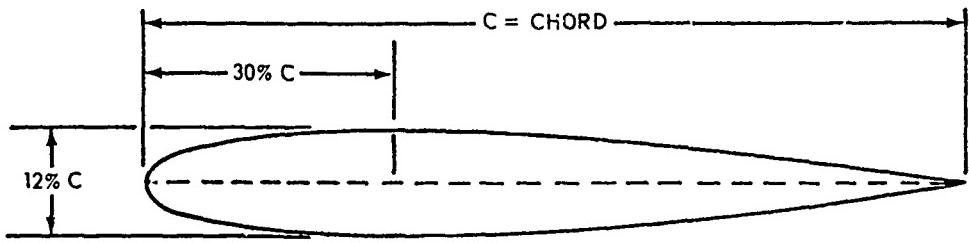
Figure 9 — NACA 0012 airfoil.

airfoil section to use in the design of rotor blades for a helicopter? If you choose the high speed airfoil section and if you further stipulate that it is to be the NACA 0012 airfoil which is a double convex section having equal and symmetrical curves or camber above and below the chord line, you have chosen well. In the above mentioned airfoil, illustrated in Figure 9, the NACA stands for the National Advisory Committee for Aeronautics. This airfoil has its greatest thickness at 30% of the chord length behind the leading edge. The figure "12" in the designation indicates that the thickness of the airfoil is 12% of the chord length at the 30% chord point. The double zeros indicate a symmetrical airfoil.

Even though the symmetric l airfoil section does not have the greatest camber on its top surface as does the general purpose airfoil, it will produce a pressure differential so long as it is flown at an angle of attack. Figure 4 illustrates a symmetrical airfoil under lift-producing conditions.

The NACA 0012 series is widely used in the helicopter industry because this airfoil section affords the best lift-drag ratio for the full range of velocities from rotor blade root to tip. This is quite important when it is realized that tip velocities may exceed 500 miles per hour. Keep in mind that induced drag varies as the square of the speed. It can be seen that for maximum efficiency of the entire blade we would want an airfoil which is efficient at the low speeds found at the root of the blade as well as the high speeds encountered at the tip.

From our discussions thus far, we know that as the angle of attack changes, the distribution of the individual forces over the surfaces of the airfoil changes. This causes the resultant to act at a different location or center of pressure. With airfoils generally used in fixed-wing aircraft, changes in angle of attack result in a considerable amount of travel of the center of pressure. This is not a very serious problem with fixed-wing aircraft because longitudinal stability can be achieved in a number of ways. In the case of rotor blades which must change angle (*feather*) about a fixed axis (*feathering axis*), the problem takes on more serious proportions.

As shown in Figure 10, the lift-drag resultant intersects the chord line or center of pressure at progressively forward locations as the angle of attack is increased.
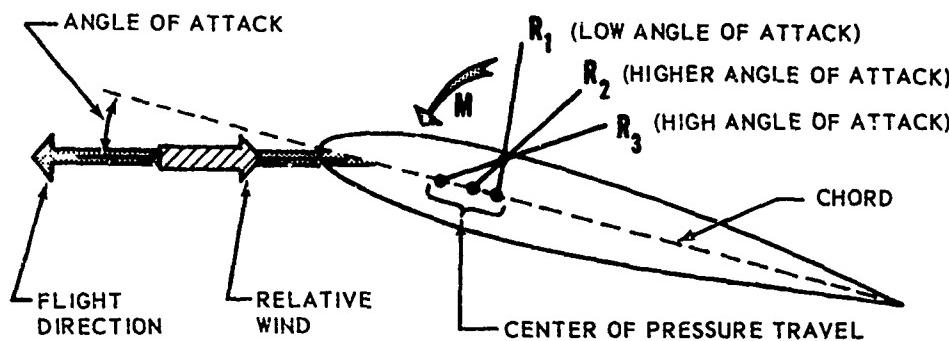

Figure 10 — Center of pressure travel.

The camber itself causes a diving moment, M, which is constant, while, with respect to a rotor blade spar within the airfoil, the lines of action through the aerodynamic center cause increasing stalling moments. It can be seen that an airfoil whose center of pressure changes with angle of attack would not be suitable for use in a rotor blade where constantly changing pitch is necessary for most directional flight speeds. Such instability would cause many complications and undesirable control forces. These complications are essentially eliminated by a symmetrical airfoil section whose aerodynamic center and/or center of pressure is always located on the median line and whose feathering axis and chordwise center of gravity are located at the same point. This is illustrated in Figure 11.
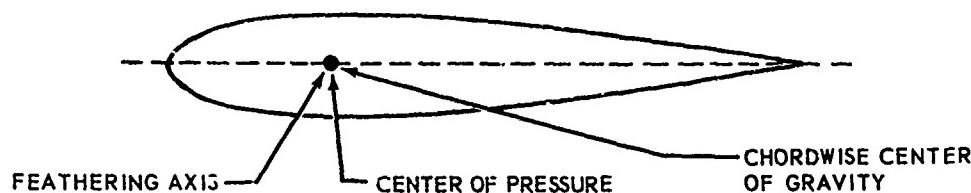
Figure 11 — Center of pressure of NACA 0012 airfoil.

It should be apparent that an airfoil with many of the important factors concerning its performance located at one point would be relatively free of any inherent moments which might be detrimental to its use as a rotor blade. In the static and aerodynamic balancing of the completed rotor blade, pitching moments are controlled and made to conform to rigid specifications in order to produce rotor blades which may be changed individually rather than in sets.

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Chapter 2

BASIC ROTARY WING THEORY
AND MAIN ROTOR CONTROL

Fortunately, there is no rule of aerodynamics which requires an airfoil to be flown in a straight line in order to perform its aerodynamic functions. The flight of a wing or a blade in a circular path around a driving shaft violates no principle discussed up to this point. The rotating rotor blade requires the same basic conditions to produce lift as the fixed wing flying in a straight line. Naturally, the helicopter rotor system will be subjected to the forces and moments peculiar to all large, rotating masses. For each of these which might produce adverse effects on the helicopter, however, there has been a substantially successful containment. As these present themselves in the text, they will be fully discussed.

Figure 12 — Rotor at rest.

In Figure 12 the diagram shows a main rotor shaft with two rotor blades located 180 degrees apart. The rotor is at rest and the two blades, due to the moment caused by their span and weight, are bending downward.

Figure 13 — Rotor turning.

In Figure 13 the main rotor shaft is turning and the blades are flying horizontally. Blade droop has been overcome by centrifugal force. We will assume that the blades are non-twisted and that they are flying at zero angle of attack. Only centrifugal loadings are experienced at this time. (Aerodynamically, of course, they are also being subjected to profile drag but we will ignore this for the time being).

In Figure 14, utilizing a shaft as an index or reference point, we have shown a horizontal force vector indicating centrifugal loadings. As a mat-

Figure 14 — Centrifugal force.

ter of interest, total centrifugal loadings on each rotor blade vary, depending on the helicopter model, from approximately 21,000 pounds to approximately 70,000 pounds, with rotor systems currently being designed to withstand loadings of 100,000 pounds.
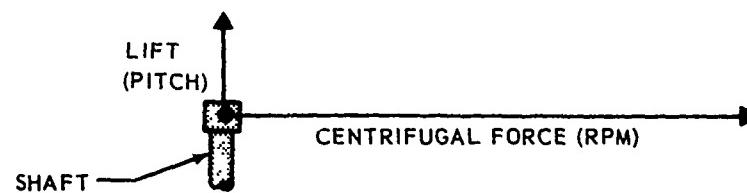

Figure 15 — Lift and centrifugal force.

Figure 15 shows a vertical force vector originating at the shaft or reference point. To produce this vertical force, we have caused our rotor blades to assume a positive pitch angle and, consequently, a positive angle of attack. The blades are no longer being acted upon solely by centrifugal force. They are also producing lift. Although one end of the rotor blade is attached to the shaft or hub assembly, the other end is free to respond to any force acting upon it. When two forces act upon one body, that body, if free to move, will assume a position dictated by the direction and magnitude of the two forces acting upon it. As stated, the rotor blade is attached at one end, but is free to move at the other end. It will thus assume the position of a resultant between the two forces acting upon it. This is shown in Figure 16, with the lift force exaggerated in order to present a clear departure of the resultant from the horizontal.
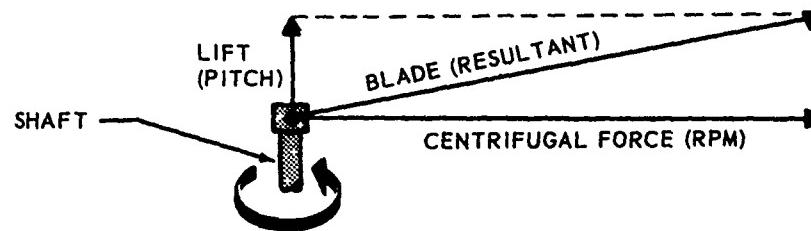

Figure 16 — Resultant of lift and centrifugal forces.

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It can be seen that because centrifugal loading is the predominate force acting upon the blade, it will assume a position closer to horizontal than to vertical. The vertical force (lift) is considerably less than the horizontal force (centrifugal). Figure 16 is, of course, not in proper proportion in that the lift being supplied by one blade is only about seven percent of the centrifugal loading on the blade. Assuming a gross weight of 18,000 pounds and a five blade main rotor system, each blade of the helicopter, while hovering with a load factor of one, would be producing a total of 3600 pounds of lift. With a total centrifugal loading at the shaft end of the blade of approximately 50,000 pounds, the departure of the resultant from horizontal would be approximately as shown in Figure 17.
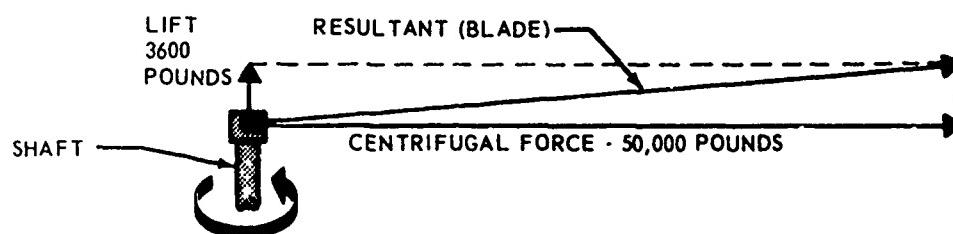
Figure 17 — Lifting rotor blade.

Having shown by the preceeding figures that a hinged rotor blade being acted upon by two forces, one approximately horizontal and the other approximately vertical, will assume the position of a resultant of these two forces, let us now return to our illustration of a main rotor shaft with two blades 180 degrees apart, and show them responding to both centrifugal and lift forces. This is shown in Figure 18.
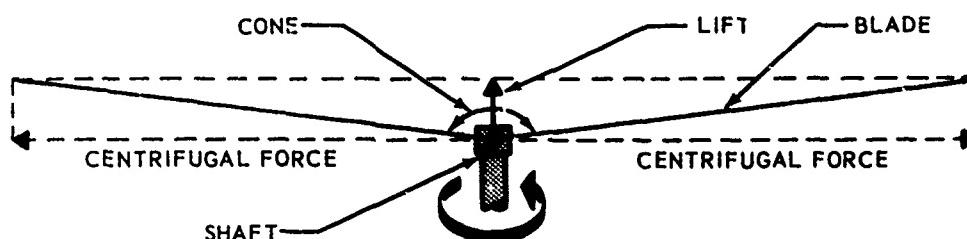
Figure 18 — Lifting rotor.

With reference to Figure 18, it may be seen that the rotor blades in rotation form an inverted cone with its apex centered at the main rotor shaft. This situation gives rise to the expression *"coning angle"*. In actual heli-

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copter operation, as pitch is increased in all blades simultaneously and the resulting lift forces the blades to support the weight of the helicopter, a visual rotational "disk" is formed. The disk, viewed from the side as in Figure 18, is easily recognized as a cone. The dotted line connecting the tips of the blades is also visually discernable and is known as the *"tip path plane"*.

TIP PATH PLANE
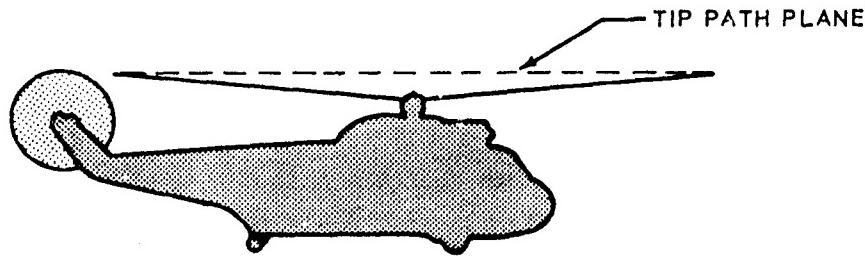
Figure 19 — Hovering helicopter at light weight.

In Figure 19, let us assume that the helicopter is lightly loaded and is hovering. The coning angle is not large as the blades are not supporting excessive loads nor is the helicopter climbing. The rotation of the blades is producing a substantial amount of centrifugal loading and the combination of light load, no climb, and normal RPM will maintain the coning angle at a relatively low value.
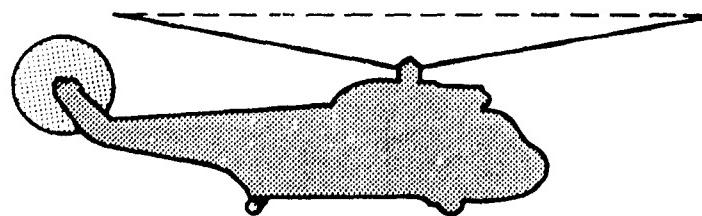
Figure 20 — Hovering helicopter at heavy weight.

In Figure 20 let us assume that the helicopter is heavily loaded and is hovering with considerable power output. The coning angle has increased because the blades are supporting more weight. Referring to Figure 17, it can be seen that if the blade is made to support more weight, more lift will be required. The vertical component vector (lift) will become longer (of greater magnitude) while centrifugal loading remains substantially constant. The resultant of these two forces moves upward. Because the resultant corresponds to the blade, it is seen that the coning angle increases with greater rotor loads. Conversely, if rotor loads remain the same but

RPM is increased or decreased, the increased or decreased centrifugal loadings would also cause changes in the direction of the resultant. It should also be mentioned that any flight maneuver which puts a "G" load or increased "load factor" on the aircraft, will cause a higher coning angle.

By this time, you have probably noticed what could be considered a contradiction between text and drawings, in that Figure 19 is said to show a rotor with a low coning angle while Figure 20 illustrates one with a high coning angle. If we were to measure the *abtuse* angle between the blades we would see that just the reverse is true, for in Figure 19 —— the angle is greater than one in Figure 20. The explanation for this apparent conflict is quite simple. Common usage of the term "coning angle" by maintenance and flight personnel implies that when the blades move upward under load, the coning angle has *increased*. When the disk flattens out, the coning angle has *decreased*. To support common usage of the term let us define it as the angle formed between the blade and the tip path plane. Figures 19 and 20 are shown with this definition in mind.

From previous discussions we know that when an airfoil is passed through the air at a positive angle of attack and with sufficient speed, it will produce lift. We can thus say that each blade in a rotor system supplies its share of the required lift. Diagramatically and practically, we can say that the total lift of the rotor may be considered to be acting from its center or virtual axis and that the total lift of the rotor always acts perpendicular to its plane of rotation. This relationship is shown in Figure 21.
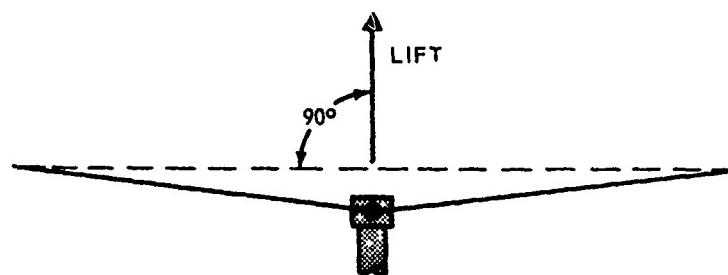
Figure 21 — Lifting rotor with thrust vector.

The 90 degree relationship between the total lift force and the plane of rotation cannot change appreciably. If the plane of rotation is made to tilt, the total lift force will tilt accordingly.

Up to this point, we have referred to the support force generated by the rotor as lift. While such terminology is perfectly satisfactory, there is another way of expressing the support force in a rotor system. The rotor is,

after all, comparable to a large, multi-bladed propeller and we have been used to referring to the force created by a propeller as "thrust". The fact that a helicopter rotor rotates more or less horizontally and generates a force which is more or less vertical does not preclude our calling the force "thrust". Academically, we may call the force generated by a helicopter rotor either 'lift or thrust. For simple discussions of rotary wing flight theory, the term "lift" is quite satisfactory. For discussions with reference to the power required for various phases of rotor operation, "thrust" might be more appropriate.

We are all familiar with this basic formula:

$$F = MA$$

FORCE EQUALS MASS TIMES ACCELERATION

Stated simply for our purpose, it means that the desired force of a rotor, *thrust*, is the product of the *acceleration* of a *mass* (air). Other thrust-producing mechanisms are covered by the same formula. An aircraft gas turbine engine achieves its thrust by giving great acceleration to reasonable quantities of air. An aircraft propeller, compared to the jet engine, produces thrust by giving a lesser amount of acceleration, but to greater quantities of air. If the propeller shaft is then rotated upward until its plane of rotation is horizontal it becomes, in essence, similiar to a helicopter main rotor. The helicopter main rotor produces thrust by giving even less acceleration, but to vastly greater quantities of air.

From the discussion in the preceeding paragraph, it may be seen that if a rotor system with its plane of rotation horizontal can be supplied with sufficient power or torque, a substantial amount of air (*Mass*) can be given sufficient *Acceleration* to produce the necessary amount of thrust (*Force*) to lift a helicopter off the ground. As valuable as this capability is, this purely vertical flight ability is not enough. A machine capable of only vertical flight would be of limited value. A directional capability is also required.

The autogyro was a partial answer to the problem. By propeller thrust it achieved a directional capability but, except for momentary ability through use of the "jump" takeoff, it lacked the true vertical capability we require. Ideally, the rotor should be capable of producing both vertical and horizontal thrust. Let us see how this is accomplished.

In Figure 21 we see that the lift or thrust of the rotor is perpendicular to the plane of rotation. It was stated that lift or thrust always remains perpendicular to the plane of rotation regardless of whether the rotational plane remains level or is inclined. In other words, if the rotor were made to tilt, the lift or thrust vector would also tilt. This is shown in Figure 22.

17
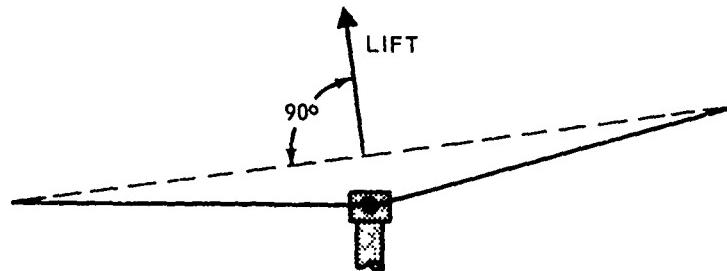
Figure 22 — Tilting rotor with thrust vector.

If the lift vector is broken down into components perpendicular and parallel to the ground as shown in Figure 23, there will be a generally vertical thrust component to support the helicopter, and a generally horizontal thrust component producing directional flight. The helicopter will move in the direction of rotor tilt.
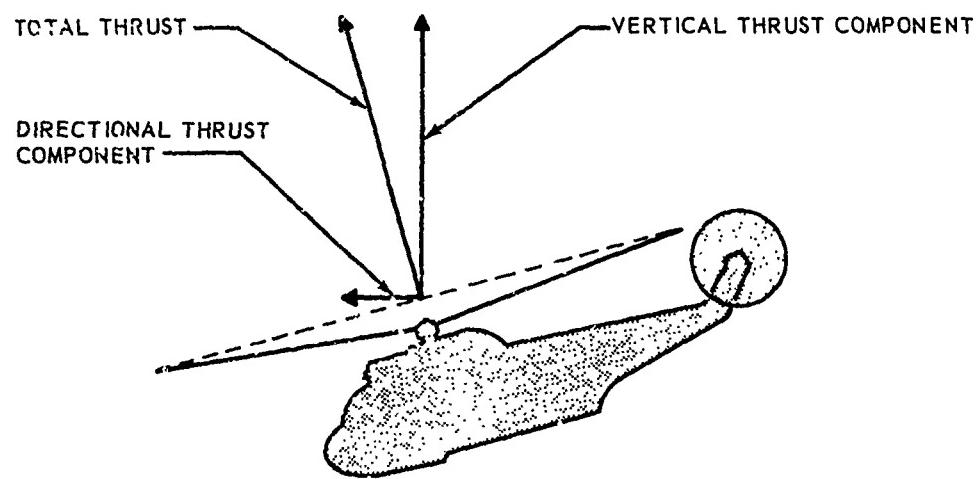
Figure 23 — Helicopter in forward flight.

For a graphic solution of how the directional thrust component is created, let us assume, as shown in Figure 24, that the total thrust created by rotor under given power and airspeed conditions is 10,000 pounds and that the rotor tilt is 15 degrees in the direction of flight. This means that the virtual axis or thrust vector of the rotor is inclined 15 degrees from vertical.

Let us lay off the 10,000 pounds in 2,000 pound increments on a line, AB, that is 15 degrees off vertical. Line AB represents the total thrust of the rotor. We will see that the vertical line, AC, representing the lift component, will scale to approximately 9700 pounds, while the horizontal or directional component, BC, will have a value of approximately 2400 pounds.
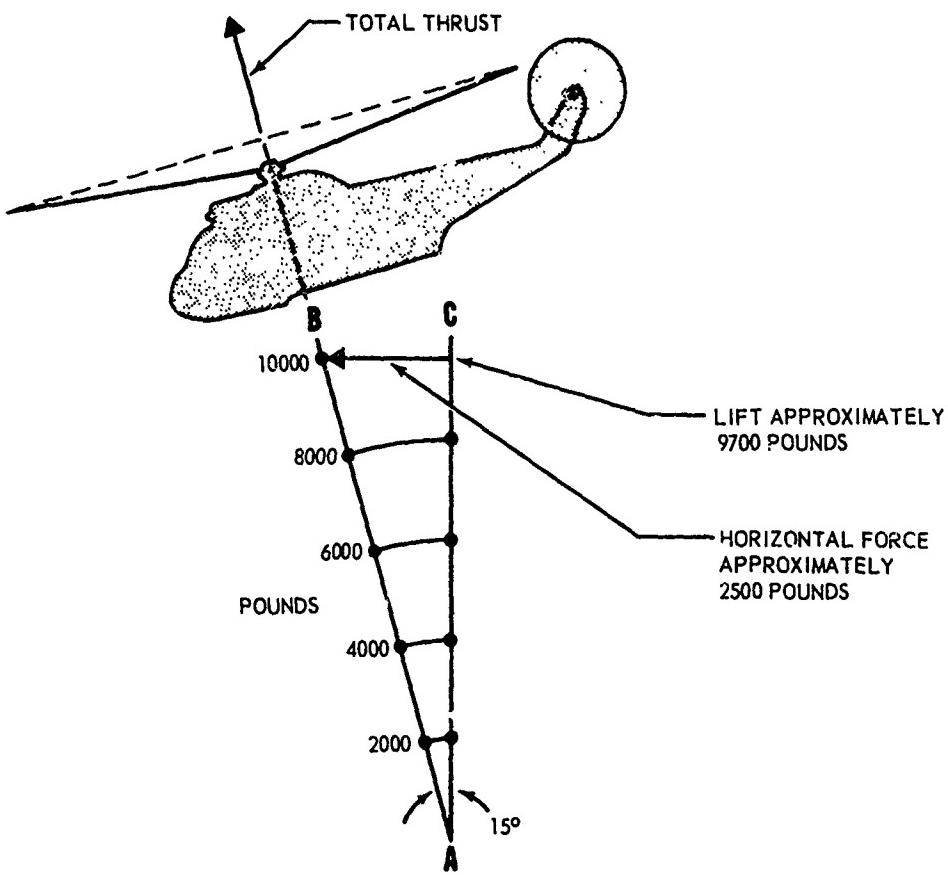
Figure 24 — 10,000 pound thrust at 15 degrees.

An easier and quicker method of solving the problem is by trigonometry. In this solution, shown in Figure 25, the formula would be:

Lift = 10,000 (cos 15 degrees)
Horizontal Force = 10,000 (sin 15 degrees)

OR

Lift = 10,000 (0.966) = 9660 Pounds
Horizontal Force = 10,000 (0.259) = 2590 Pounds

LIFT = AB (COS 15°)

HORIZONTAL FORCE = AB (SIN 15°)

AB = 10,000 LBS
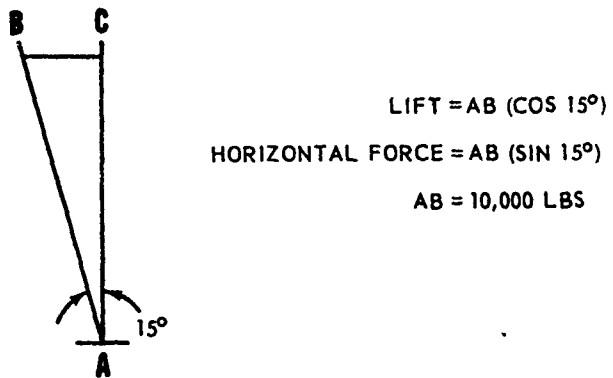
Figure 25 — Trigonometric solution of rotor lift.

Reference to either the graphic or trigonometric solution of the problem indicates that the greater the tilt of the rotor, the greater the horizontal force and, assuming that power settings and airspeed remain constant, the smaller the lift force.

The directional force component is, of course, opposed by the aerodynamic drag of the helicopter. As long as the horizontal force component is greater than the drag, there will be directional acceleration. As drag increases with increased speed, it will eventually equal the directional force and uniform speed will result. The same is true of the lift component. When the lift and gravity forces equal each other, the helicopter remains at a constant altitude. A change in either of the two forces will cause either climb or descent.

With the realization that tilting the thrust vector or virtual axis of the rotor introduces a directional component there were, in the early days, many novel ideas conceived to produce a rotor tilt. Undoubtedly there were attempts to tilt the entire power package including transmission and rotor head in an effort to tilt the rotor. These ideas were soon given up in favor of aerodynamic rather than mechanical tilting.

Let us analyze what had to be accomplished to produce a rotor tilt.

THRUST VECTOR
(VIRTUAL AXIS)
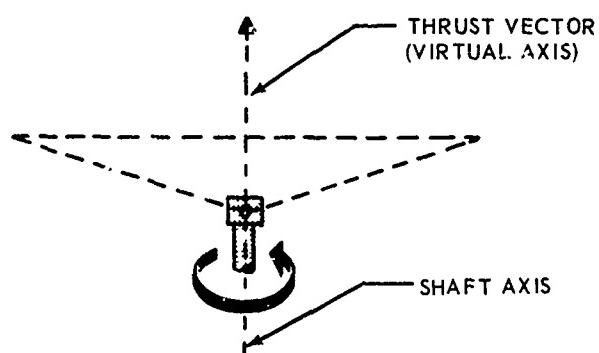
SHAFT AXIS

Figure 26 — Rotor thrust on shaft axis.

The dotted outline of a rotor and rotor shaft is shown in Figure 26. The rotor is turning as evidenced by a coning angle. Power is being applied. The thrust vector (virtual axis of the rotor) and the rotor shaft axis are the same.

In Figure 27 notice that in the dotted rotor, just as it was shown in Figure 26, the thrust or virtual axis of the rotor is the same as the shaft axis. In the tilted, solid-lined rotor, the thrust or virtual axis is not the same as the shaft axis even though the shaft, which remains vertical, is turning the rotor. In other words, the rotor is tilted with reference to the shaft.

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THRUST OR VIRTUAL AXIS
OF TILTED ROTOR

THRUST OR VIRTUAL AXIS OF NON-TILTED
ROTOR (SAME AS SHAFT AXIS)

B

A

SHAFT AXIS
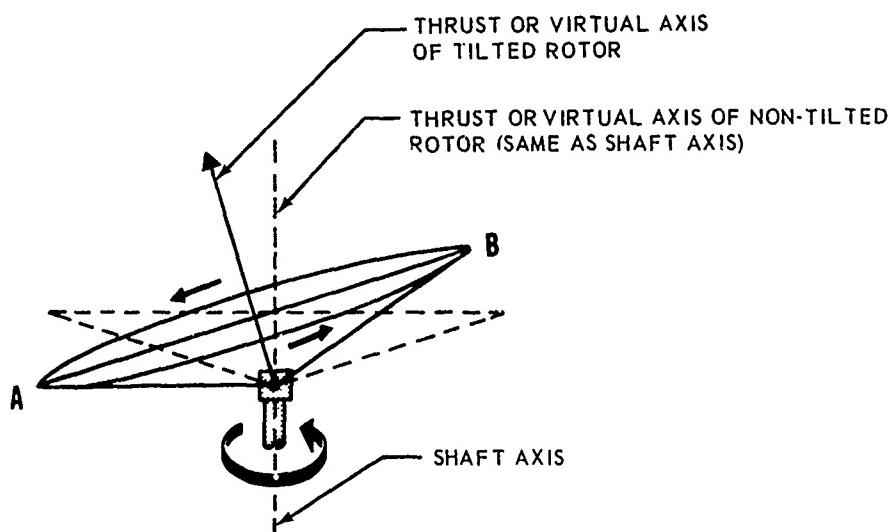
Figure 27 — Inclined thrust.

Note also that in order to achieve a rotor tilt, the blades must pass from a low point, A, to a high point, B, 180 degrees of rotation away. In other words, the blades must climb from point A to point B and then dive from point B to point A. From our earlier discussions of aerodynamics, we stated that a blade will climb or dive due to loss or gain of lift resulting from either varying airspeed or varying angle of attack. It is obvious that with regard to a rotor operating at a substantially constant RPM, deliberate changing of blade airspeed to cause climb or dive is impossible. What can be varied, however, is the angle of attack. The blades climb and dive between points A and B causing the rotor disk to tilt, due to pitch changes which result in angle of attack changes.

The blade operates at a reduced pitch when moving the 180 degrees of rotation from point B to point A. This reduced pitch causes a loss of lift which, in turn, causes the blade to settle or dive. The blade operates at an increased pitch angle when moving the 180 degrees from point A to point B. The increased pitch causes increased lift which, in turn, causes the blade to climb. With each blade in the system following the same flight path rotationally, the total effect is a tilted rotor with the total thrust of the rotor being in the direction of the lowest point of the rotor (A).

Because this method of tilting the rotor is accomplished by changing the pitch of each blade individually as it makes a complete rotation or cycle, the pitch change involved is called "*cyclic*" and the pitch control that governs cyclic pitch has been named the *cyclic pitch stick*. The change in blade pitch is also called "feathering". Exact methods of rotor control will be discussed later.
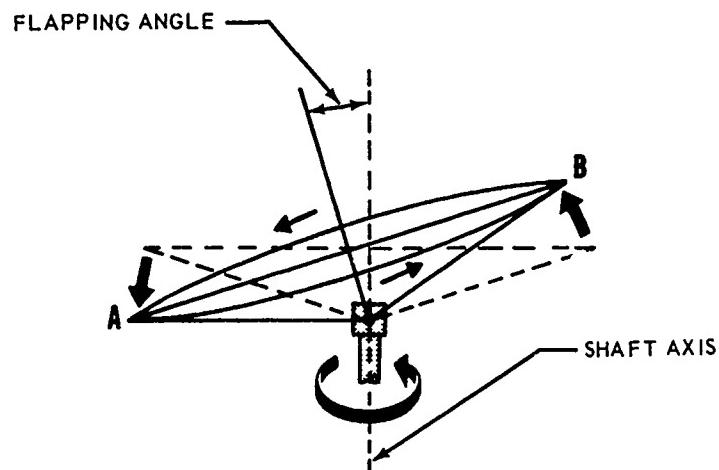
Figure 28 — Blade flapping.

It must be noted that when we tilt the rotor cyclically, the rotor axis (virtual axis) and the shaft axis no longer fall along the same line.

In Figure 28 the dotted lines represent the rotor with no tilt with reference to the shaft. The virtual axis of the rotor and the shaft axis are on the same line. When the rotor is tilted by cyclic pitch changes, the virtual axis (thrust vector) is inclined so as to remain perpendicular to the plane of rotation. This means that with respect to the rotor head, the blades must *flap* downward in moving from B to A and *flap* upward in moving from A to B. Blade flap is thus a necessity and requires a hinge at the connection between the blade and the rotor head. The angle between the shaft axis and the virtual axis of the rotor is called the *"flapping angle"*. Note that we now have two angles which are peculiar to helicopter operation. They are the flapping angle which we just discussed, and the coning angle which was discussed earlier and illustrated in Figure 18.

From the preceeding paragraphs, it is quite apparent that two types of control are necessary for the operation of the main rotor. First, we need a control to govern the *amount* of lift or thrust generated by the main rotor. Second, we need a control to govern the *direction* of main rotor thrust.

With regard to the first requirement, it stands to reason that if we can control the pitch of all the blades in the main rotor system simultaneously, we can govern the amount of lift or thrust being generated. Because this pitch increasing or decreasing action takes place on all the blades simultaneously, it may be referred to as a *collective* action. The control itself is referred to as the collective pitch control or *collective pitch stick*

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The second requirement, that of controlling the direction of main rotor thrust, is accomplished by changing the pitch of each blade individually as it rotates through one rotation or cycle. It is natural to call the control that accomplishes this change the *cyclic pitch stick*.

The mechanics of such a control system call for a collective pitch stick; a cyclic pitch stick; an element where these controls can be integrated or mixed; a non-rotating unit (stationary star) surrounding the main rotor shaft which can be raised, lowered, or tilted by action of the control sticks and a rotating unit (rotating star) attached to the non-rotating unit through bearings in order that its elevation and tilt will be identical with that of the non-rotating unit. In addition, the rotating unit must have pitch-control rods extending to each rotor blade in the system in order that the unit's elevation and tilt may be manifested in pitch changes at the blades.

Figures 29, 30, and 31 illustrate the method by which both collective and cyclic pitch is induced into the rotor blades. In Figure 29 notice that

FORWARD

PITCH CONTROL ROD

ROTATING SCISSORS

ROTATING STAR

STATIONARY SCISSORS

FORE AND AFT CONTROL INPUT FROM CONTROL STICKS VIA MIXING UNIT

LEFT LATERAL CONTROL INPUT FROM CONTROL STICKS VIA MIXING UNIT

RIGHT LATERAL CONTROL INPUT FROM CONTROL STICKS VIA MIXING UNIT

TRANSMISSION
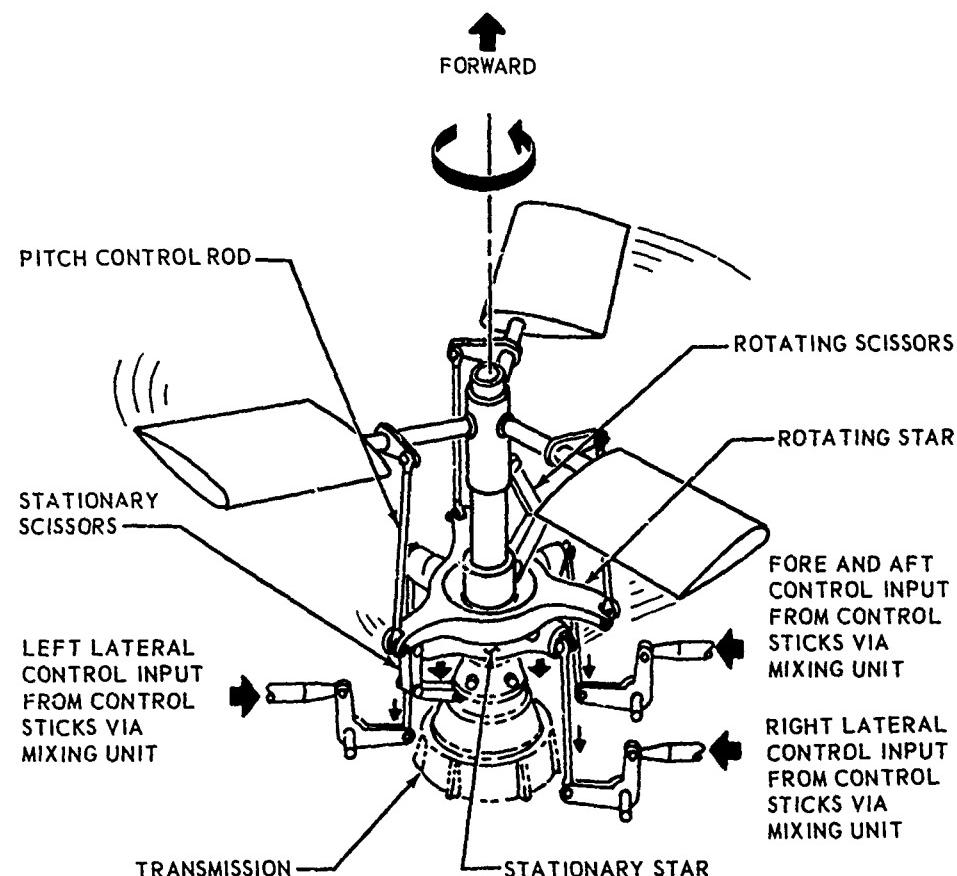
STATIONARY STAR

Figure 29 — Low pitch.

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just three (3) control rods from the control sticks (via the mixing unit) are attached to the stationary star. These input rods to the stationary star are located in positions as indicated in Figure 32.

The stationary star is actually a four-point star. Three of the points are connections for the input rods, while the fourth is reserved for the stationary scissors assembly. The stationary scissors assembly permits the star to raise, lower, and tilt according to control inputs, but will not permit it to rotate.

Figures 29, 30, and 31 illustrate the *swash plate* or *azimuth star* method of transmitting control inputs to the blades. In Figure 29 the collective pitch stick is full low and the cyclic stick is neutral or centered. The stationary star is low and level. The rotating star, being an integral though rotating part of the star assembly, is also low and level. Because all of the blade pitch control rods have been pulled downward by the star assembly, all of the blades are flying at low pitch.

FORWARD

ROTATING SCISSORS

ROTATING STAR

PITCH CONTROL ROD

FORE AND AFT CONTROL INPUT FROM CONTROL STICKS VIA MIXING UNIT

LEFT LATERAL CONTROL INPUT FROM CONTROL STICKS VIA MIXING UNIT

RIGHT LATERAL CONTROL INPUT FROM CONTROL STICKS VIA MIXING UNIT

STATIONARY SCISSORS

TRANSMISSION

STATIONARY STAR
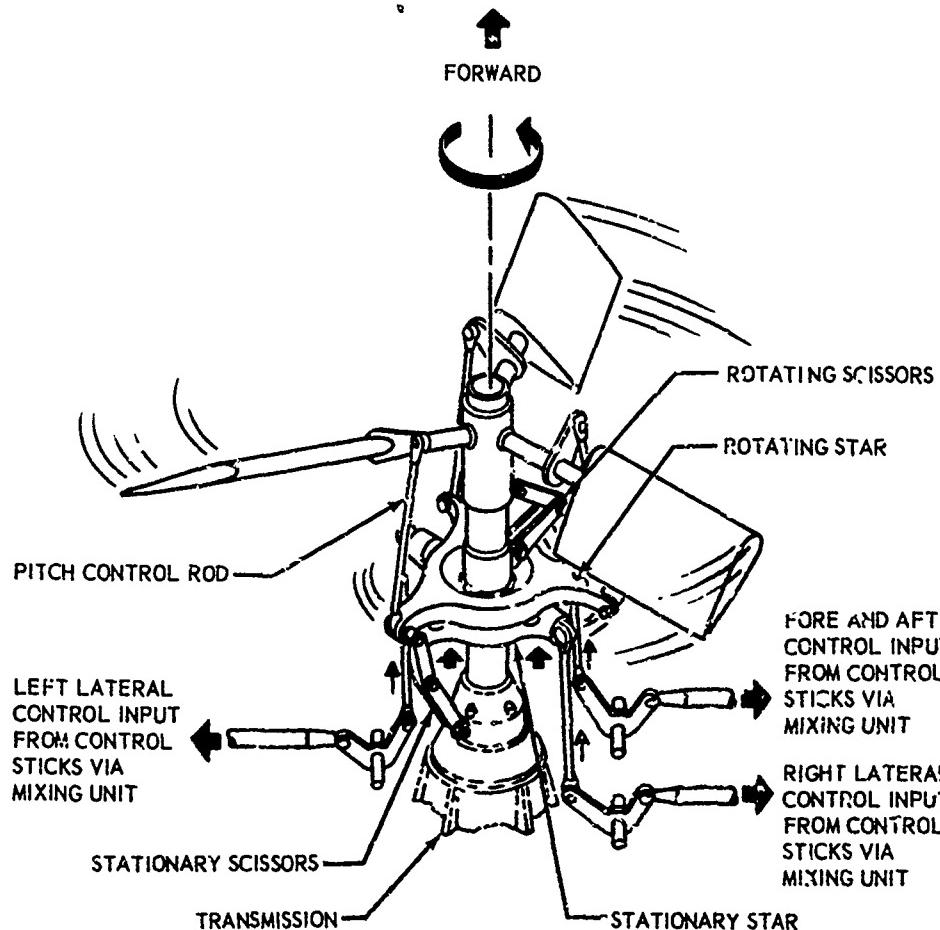
Figure 30 — High pitch.

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In Figure 30 the collective pitch stick has been raised to its full high position with the cyclic stick still neutral or centered. The star assembly, sliding upward on a ball joint on the main shaft, is now at its highest position. Because all of the blade pitch control rods have been pushed upward by the star assembly, all of the blades are now flying at high pitch.


FORWARD

ROTATING SCISSORS

PITCH CONTROL ROD

ROTATING STAR

LEFT LATERAL
CONTROL INPUT
FROM CONTROL
STICKS VIA
MIXING UNIT

FORE AND AFT
CONTROL INPUT
FROM CONTROL
STICKS VIA
MIXING UNIT

RIGHT LATERAL
CONTROL INPUT
FROM CONTROL
STICKS VIA
MIXING UNIT

STATIONARY SCISSORS

TRANSMISSION
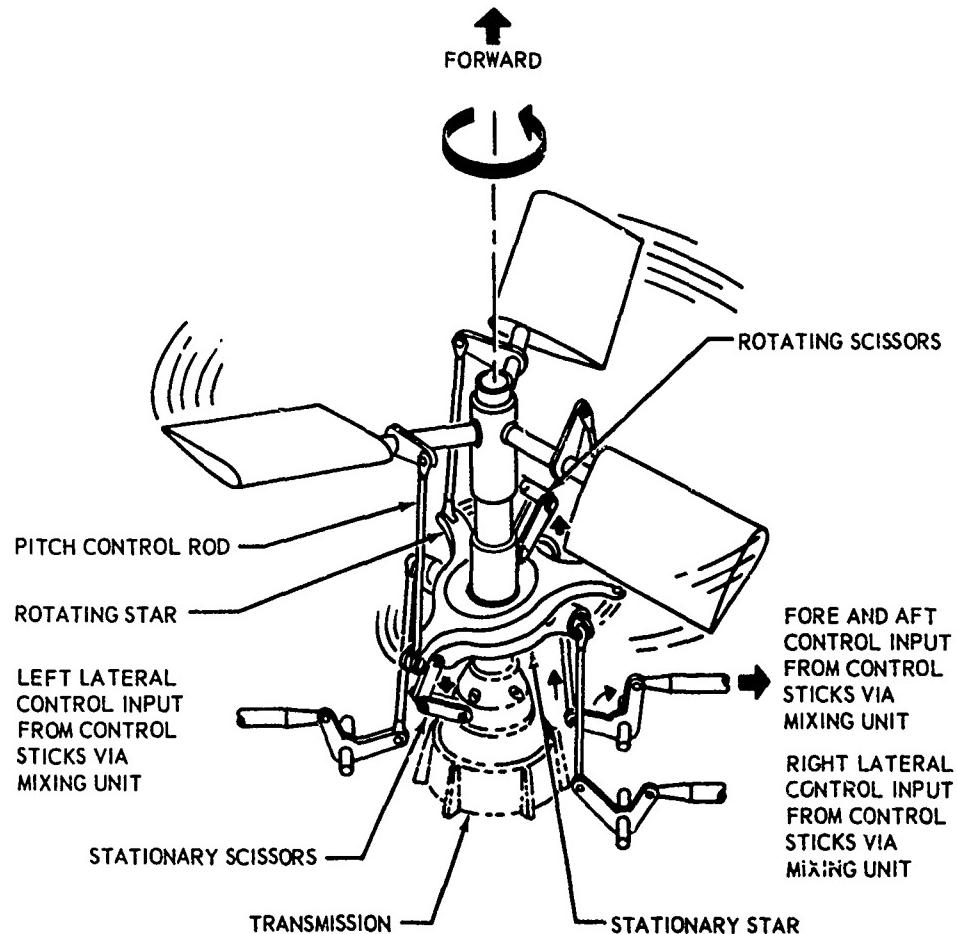
STATIONARY STAR

Figure 31 — Cyclic pitch.

Figure 31 shows the star assembly tilted due to cyclic stick action. The cyclic stick has been pulled AFT, pushing up on the fore and aft rod (servo). The left and right lateral rods (servos) remain stationary thus forming the pivot point for the tilting action. The lowest point of the tilted star assembly is over the stationary scissors assembly while the highest is over a position 180 degrees opposite or at the fore and aft rod (servo.) This means that the rotating star is now rotating in an inclined circle and as the blade pitch control rods rotate, they are constantly undergoing an up and down motion. Because these rods are attached to the rotor blades,

25
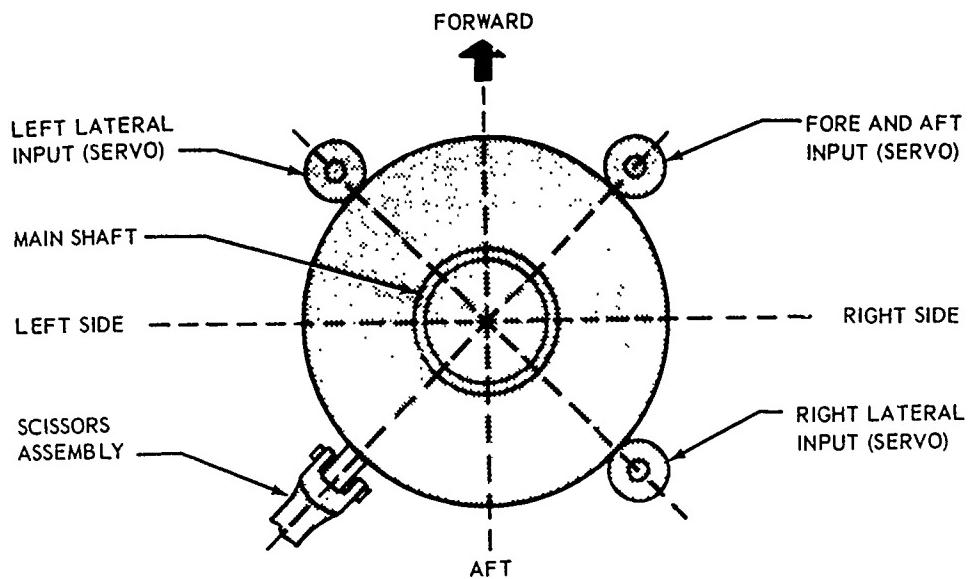
Figure 32 — Rotor control input locations.

it is seen that the blades are constantly undergoing pitch change — changing from a high value to a low value once each revolution. As discussed previously, these pitch changes cause the blades to climb and dive, thus tilting the rotor.

It should also be stated that by means of the mixer or mixing unit, both cyclic and collective control may be utilized in any combination or mixture desired. If cyclic stick is being applied for directional flight, the addition of collective pitch does not (except in control systems employing lateral lead) change the tilt of the star and/or rotor. It simply moves the star upward so as to increase the pitch on all blades simultaneously thus producing more thrust in the direction dictated by the tilt of the rotor. Lateral lead, a control system bias, will be explained later in the text.

We have stated that by means of cyclic pitch change, we make the blades climb from point A to point B and then dive from point B down to point A. In so doing we effectively tilt the rotor in the direction of desired flight. In order for the blade to pass through points A and B, as shown in Figure 33, it is obvious that they are going to have to flap up and down on a hinge.

One might be led to think that at point A where the blades are at their lowest flapping point, they would also be at their lowest pitch. And that at point B where they are at their highest flapping point, they would be at their highest pitch. If only aerodynamic considerations were involved in the statement, it could be considered as true. A rotor system, however, has the qualifications necessary to take on certain properties of the gyroscope.

26
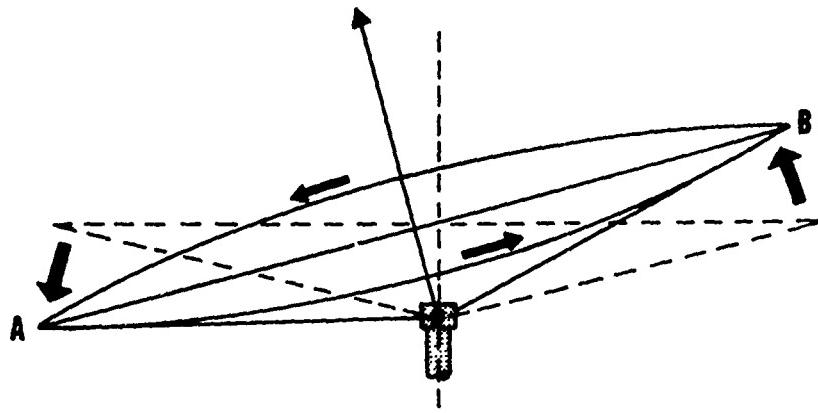
Figure 33 — Hinged rotor with flapping blades.

While we are not necessarily interested in the gyroscope's property of rigidity in space, we are most interested in its property of precession.

Gyroscopic precession is an inherent quality of rotating bodies in which an applied force is manifested 90 degrees in the direction of rotation from the point where the force is applied.
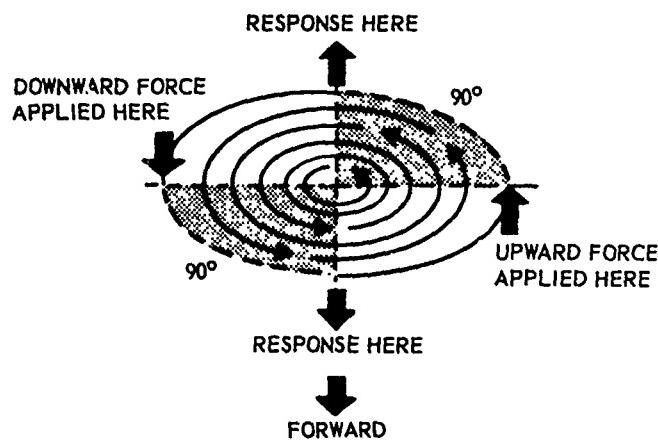
Figure 34 — Gyroscopic precession.

Considering a rotating disk turning counter-clockwise as shown in Figure 34, a downward force applied to the side of the disk would cause the disk to tilt downward 90 degrees of rotation from the point where the force was applied. Thus, to achieve a forward rotor tilt in a counter-clockwise rotor system, the force causing the blades to flap downward over the nose must be applied to the rotor on the right side of the helicopter while the force causing the blades to flap upward over the tail must be applied on the left side of the helicopter. 90 degrees of rotation from where the

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forces were applied, the blades will flap to their highest and lowest position. The "force" referred to is, of course, pitch change. The same is true of a tilt in any direction. The cyclic pitch causing blade flap must be placed on the blades 90 degrees of rotation before the lowest and highest flap are desired. Precession of the rotor is taken into consideration by the controls designer. His design insures that when the pilot pushes the cyclic stick forward the action will tilt the star assembly so as to place the lowest cyclic pitch on the blade over the right side of the helicopter, and the highest cyclic pitch on the blade over the left side of the helicopter. The rotor will always tilt in the direction in which the cyclic stick is moved.

With reference to Figure 32, which shows star control input positions, the reader might wonder why the star input rods (servos) are located at 45 degree angles to the longitudinal and lateral axes of the aircraft.

AFT   LEFT-HAND SIDE

HORN ASSEMBLY

FORWARD

RIGHT-HAND SIDE

SHAFT

PITCH CONTROL ROD
LEADS BLADE BY ABOUT
45° VIA HORN ASSEMBLY
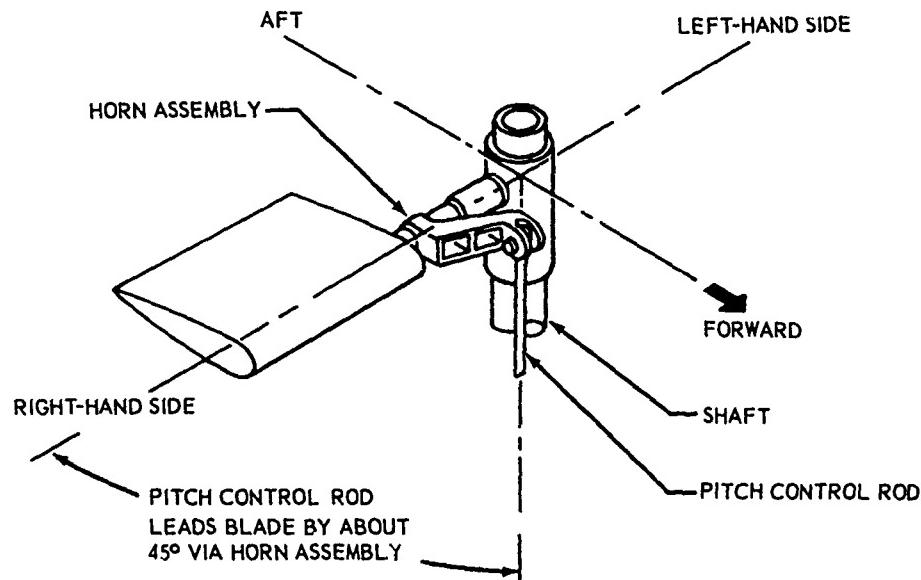
PITCH CONTROL ROD

Figure 35 — Blade pitch control linkage.

In Figure 35 it may be seen that the horn assembly forms a lever which affords the pitch control rod a mechanical advantage when rotating the blade about its sleeve bearirgs. If, by use of the horn assembly, the pitch control rod is going to lead the blade by about 45 degrees, it stands to reason that the star input rod (servo) must be directly underneath the rod to control the blade's pitch at the desired point. Thus while the three star input rods (servos) are located 90 dgerees apart, they are 45 degrees to the longitudinal and lateral axes of the helicopter.

It should be noted that in preceeding paragraphs, each time the expression "star input rod" was mentioned, the word *servo* was placed after

it in parenthesis. While it is true that these input devices may be considered, as indeed they are, control rods, it is also in order to state they are hydraulically power-boosted rods or servos. In current generation helicopters of substantial size, feedback forces from the rotor system would be impossible to control by simple mechanical advantage in control sticks. Servos utilizing pressures of 1500 to 3000 PSI thus comprise our mandatory "power steering".

Through our swash plate or star assembly method of rotor control, it is easy to see how the addition of collective pitch causes greater thrust as all blades receive a pitch increase simultaneously. It might be interesting, however, to see what happens as only cyclic pitch is applied.

Before we can present a diagram showing a typical condition of cyclic pitch change, it is first required that we understand certain basic blade settings. In the flight control rigging of a helicopter utilizing the fully articulated rotor head, the blades must be set at a predetermined angle with collective pitch stick in its full low position, the star level, and cyclic pitch stick in neutral or centered.

ROTOR HEAD

PITCH CONTROL ROD (ADJUSTABLE)

BALL JOINT AND BEARING ASSEMBLY

CONTROL INPUT ROD (SERVO)

BLADE

SHAFT

ROTATING STAR

STATIONARY STAR

TRANSMISSION
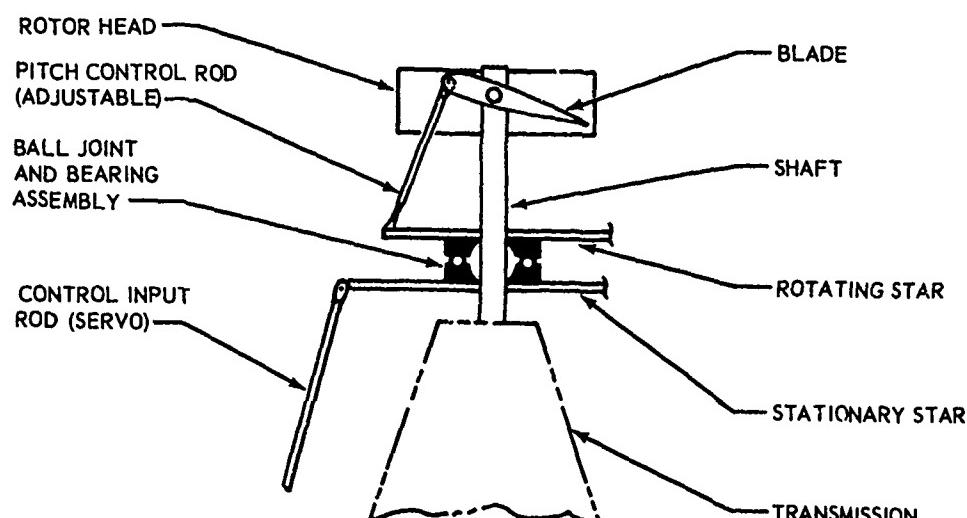
Figure 36 — Basic control and blade setting.

Figure 36 illustrates, schematically, the desired situation. We are assuming that the collective pitch stick has been placed in its full low position, thus pulling the star assembly down the shaft to its lowest point. The stationary star input rods (servos) have been adjusted to make the star assembly *parallel with the rotor head*. The cyclic stick is in neutral (centered) so that the star has no tilt. The pitch control rods are then adjusted to place the rotor blade angle at (and this figure would vary somewhat on different model helicopters) approximately 8 degrees above a

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plane parallel with the rotor head and star assembly. The required angle is chosen because it will produce normal autorotation RPM considering blade twist. This particular consideration will be discussed fully later on in the text. With the above in mind, we can now have a detailed look at cyclic pitch.
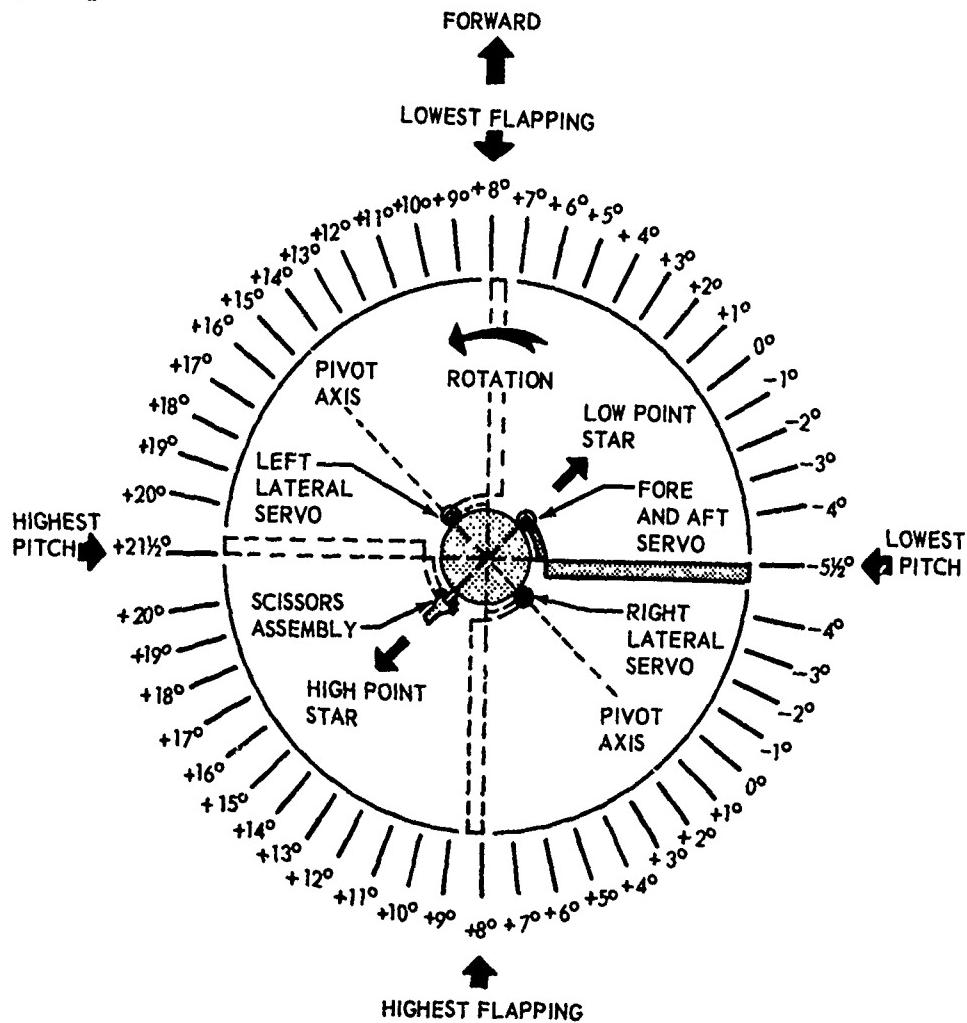
Figure 37 — Cyclic pitch variation — full forward, low pitch.

In Figure 37 we are looking down on the rotor disk. We see the location of the fore and aft, left, and right lateral servos (star input rods). We see a rotor blade over the right side of the helicopter with its horn assembly leading it by about 45 degrees to a point over the fore and aft servo. In other words, the pitch change rod of the blade is directly over the fore and aft servo — the pitch change being fed back to the blade through the horn assembly.

We are now going to examine pitch change as it takes place with the cyclic stick moved to its full forward position. Remembering that for

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forward flight we need a low angle on the blade when it is on the right side of the aircraft and a high angle on the blade when it is on the left side of the aircraft because of the 90 degree force-displacement phasing, it is obvious that forward movement of the cyclic stick will pull the fore and aft servo downward thus pulling down on the blade pitch control rod and rotating the blade on its sleeve bearings to a low pitch angle which is dictated by the limitation of stick travel. Because we moved the cyclic stick forward only, with no movement to the left or right, it may be seen that the star assembly is tilted low over the fore and aft servo and, pivoting on the motionless lateral servos, high over the scissors assembly. This means that when the pitch control rod of *any* blade is over the fore and aft servo, that blade, travelling 45 degrees of rotation in back of its pitch control rod, will be at its lowest pitch. Conversely, when the pitch control rod of any blade is over the scissors assembly, that blade, travelling 45 degrees of rotation in back of its pitch control rod, will be at its highest pitch.

Utilizing the rigging figures of a current Sikorsky helicopter as an example, forward movement of the cyclic stick has placed the pitch of the reference blade over the right side of the helicopter at minus $5\frac{1}{2}$ degrees below a plane parallel to the rotor head and star assembly.

Let us now move the reference blade in the direction of rotation. As we move the blade forward, its pitch control rod leaves its point over the low point fore and aft servo. As the rotating star rotates toward the left lateral servo which has moved neither up nor down, it is rotating upward on an inclined plane. In so doing it pushes upward on the reference blade's pitch control rod. The blade, in turn, is increasing pitch. 90 degrees of rotation later, with the blade over the nose of the helicopter, the blade's pitch control rod is over the left lateral servo and the blade pitch now reads plus 8 degrees even though it has flapped to its lowest point over the nose.

As we continue to move the reference blade around to the left side of the helicopter, the star and the blade's pitch control rod continue to move upward until they are directly over the scissors assembly with the blade at the left side of the helicopter. At this point the blade pitch reads plus $21\frac{1}{2}$ degrees. If you wonder how we derived the plus $21\frac{1}{2}$ degree figure, just remember that with the cyclic stick in neutral, all blade angles were plus 8 degrees. Moving the cyclic stick forward made the blade on the right side of the helicopter reduce pitch to minus $5\frac{1}{2}$ degrees — a pitch change of $13\frac{1}{2}$ degree *below* the neutral reference of plus 8 degrees. It stands to reason that the blade on the left side of the helicopter would have a reading of plus $21\frac{1}{2}$ degrees, $13\frac{1}{2}$ degrees *above* the neutral reference of plus 8 degrees.

Moving the reference blade to a position over the tail of the helicopter brings the star and pitch control rod of the blade over the right lateral servo. Here the blade angle reads plus 8 degrees just as it did over the nose of the aircraft. At this point, however, it will be at its maximum upward flapping point. Another 90 degrees of rotation brings it back over the right side of the helicopter where its angle will again read minus 5½ degrees.

With cyclic stick full forward we can determine the amount of pitch change the blades undergo in 360 degrees of rotation by adding the lowest pitch (minus 5½ degrees) to the highest pitch (21½ degrees). The total pitch change in one rotor revolution is thus 27 degrees. Because one degree of cyclic pitch may be said to cause approximately one degree of rotor tilt, we have available about 13½ degrees of effective cyclic control or rotor tilt in the forward direction. This amount of control is ample.
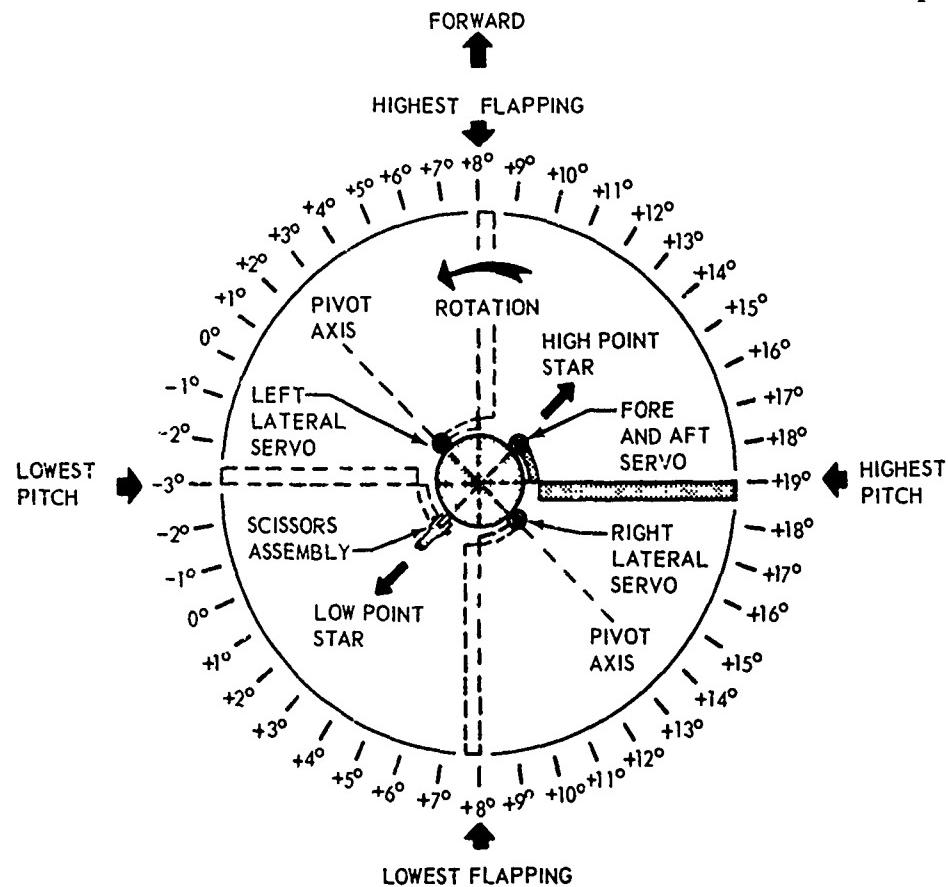
*Figure 38 — Cyclic pitch variation — full aft, low pitch.*

Figure 38 shows the situation when the cyclic stick is pulled all the way aft. Still pivoting on the two lateral servos, the fore and aft servo has now pushed the star and blade pitch control rod upwards. Naturally the low

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point of the star is over the scissors assembly. The angle of the reference blade on the right side of the helicopter now reads plus 19 degrees. Just as we did for forward stick in Figure 37, we may now trace the aft stick progress of the blade through one revolution of the rotor.

Over the nose of the helicopter the reference blade will flap highest even though its pitch has returned to plus 8 degrees. Over the left side of the helicopter the blade angle will read minus 3 degrees because its rod is over the scissors assembly which is the lowest point of the star. Over the tail of the helicopter the blade will be flapping to its lowest point even though its angle, due to its rod being over the right lateral servo, will read plus 8 degrees. Another 90 degrees of rotation brings it to its starting point and the original angle of plus 19 degrees. Full aft stick produces a total pitch change of 22 degrees and about 11 degrees of effective cyclic pitch control or rotor tilt aft. This amount of aft control is ample.

Lateral control of the rotor differs from fore and aft control in that moving the cyclic pitch to the left or right activates the two lateral servos instead of the fore and aft servo. As illustrated in Figure 39, the fore and aft servo and the scissors assembly now become the pivot points for the star. The lateral servos now work simultaneously but in opposite directions.

In discussing lateral control, we now have a new starting position for the reference blade. It is directly over the nose of the aircraft with its pitch control rod over the left lateral servo. When we push the cyclic stick to the left, control linkage causes the left lateral servo to move downward and the right lateral servo to move upward. The blade, with its rod over the left lateral servo, will experience a decrease in pitch because its pitch control rod was pulled down. With full left cyclic stick the blade angle will read minus 1 degree.

With the reference blade rotated until it is over the left side of the helicopter and its pitch control rod over the scissors assembly, its angle will read plus 8 degrees and it will be at its lowest flapping point. Over the tail of the helicopter the blade angle will be plus 17 degrees because its pitch control rod will be over the right lateral servo — the high point of the star. Over the right side of the helicopter the blade angle will have returned to plus 8 degrees, but it will be at its highest flapping point. Over the nose of the helicopter the angle will again read minus 1 degree. Full left cyclic stick produces a total pitch change of 18 degrees which amounts to about 9 degrees of effective cyclic pitch control or rotor tilt to the left. This amount of left rotor control is ample.

Moving the cyclic control stick to the right causes the left lateral servo to move upward and the right lateral servo to move downward. The refer-
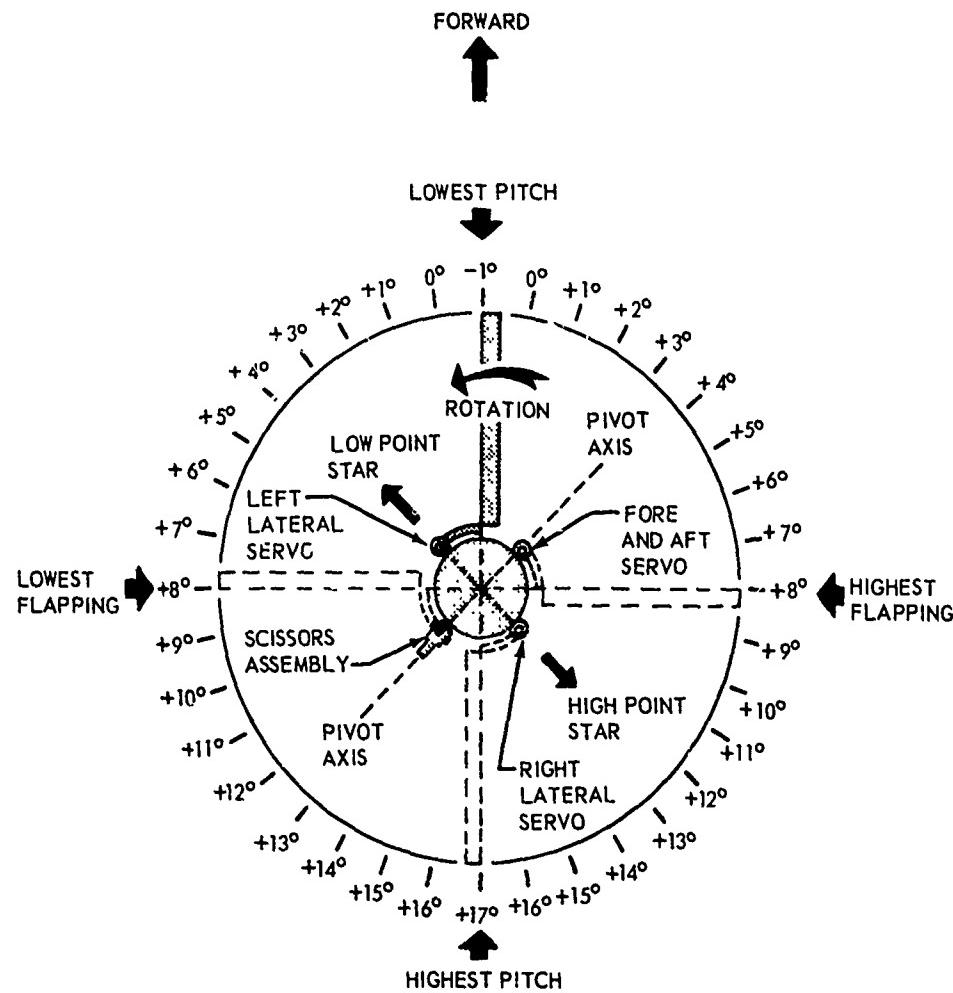
Figure 39 — Cyclic pitch variation — full left, low pitch.

ence blade, with its pitch control rod still over the left lateral servo, will experience an increase in pitch because its rod was pushed upward. With full right cyclic stick, the angle will be plus 15 degrees. As shown in Figure 40, moving the blade from the nose of the helicopter to the left side brings its pitch control rod over the scissors assembly producing an angle reading of plus 8 degrees and the blade will be at its highest flapping point. Over the tail of the helicopter the blade angle will be plus 1 degree because its pitch control rod will be over the right lateral servo, the lowest point on the star. Over the right side of the helicopter the blade angle will have returned to plus 8 degrees, but it will be at its lowest flapping point. Over the nose of the helicopter the angle will again read plus 15 degrees. Full right cyclic stick produces a total pitch change of 14 degrees which

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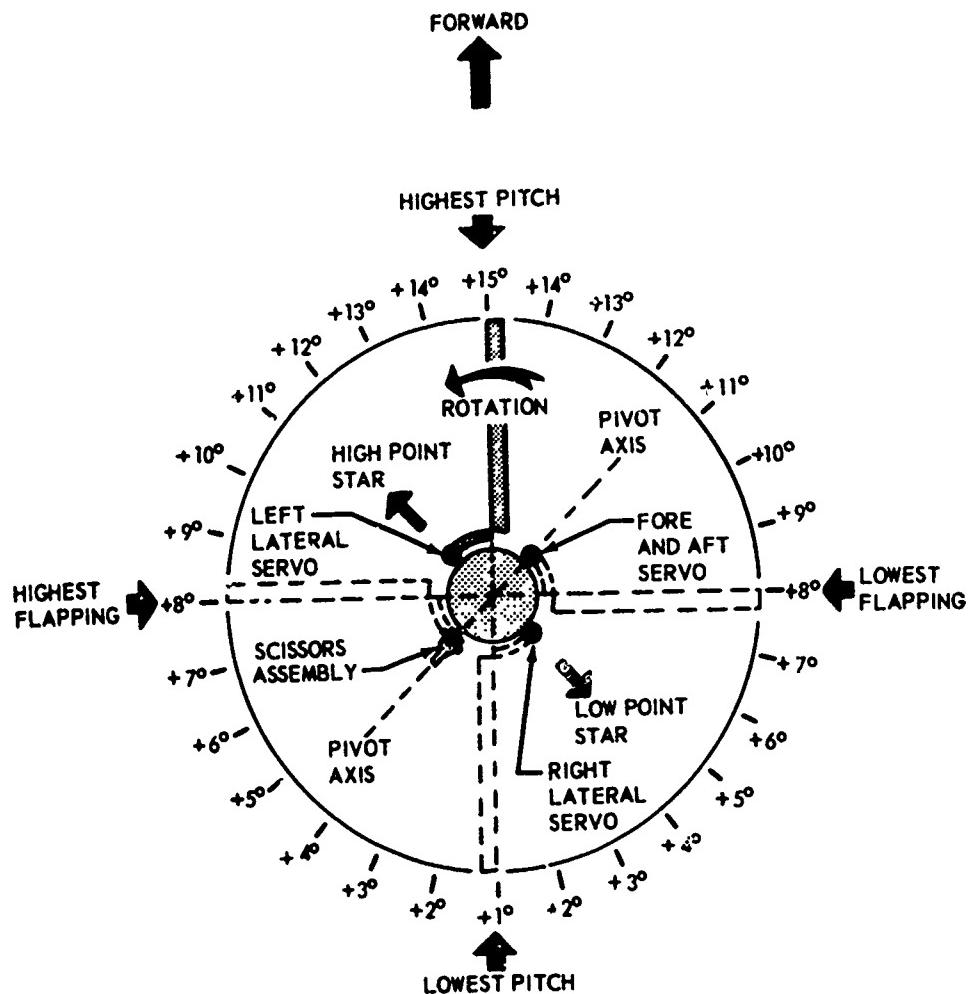
Figure 40 — Cyclic pitch variation — full right, low pitch.

amounts to about 7 degrees of effective cyclic control or rotor tilt to the right. This amount of right rotor control is ample.

Although we have discussed only fore, aft, left, and right cyclic stick control, it should be stated that the cyclic stick is not limited to these major directions. The stick may be moved or rotated in a circle and the tilt of the rotor will follow it. The rotor may be tilted in any one of 360 degrees.

A nutshell summation of what we have shown in terms of blade angle and flap may be made by stating that due to gyroscopic precession, the force (pitch change) which causes blade flap must be applied to the blade 90 degrees of rotation preceeding the point where maximum blade flap is desired. Once this is programmed into the flight control system, precession no longer remains a problem.

It should finally be stated that with the conditions shown in Figures 37, 38, 39 or 40, the addition of collective pitch generally does nothing to change the rotor tilt brought about by cyclic pitch change. If five degrees of collective pitch were added, we could simply add five degrees to each of the angular values shown in the illustrations. The addition of collective pitch influences only the amount of thrust being produced by the rotor. As previously mentioned, the only exception to this statement is that in helicopters with "lateral lead" there will be a small amount of rotor tilt associated with raising collective pitch due to a deliberate bias built into the system for the purpose of counteracting the right drift caused by the torque compensating effect of the tail rotor. This will be fully explained in the next chapter.

Chapter 3
ARTICULATION, HINGE OFFSET
AND TORQUE COMPENSATION

It was stated in our introduction that this document is basically a discussion of the flight theory, forces, phenomena, and operation of conventional, single rotor helicopters utilizing fully articulated rotor heads with offset hinges. In preceeding chapters we have discussed to some extent, two of the three degrees of articulation found in the fully articulated rotor head. First, the blade must be able to change pitch. It does this by rotating its sleeve about a spindle and an associated thrust bearing assembly. Pitch, of course, is controlled by the pilot through cyclic and collective pitch sticks. Secondly, we have seen that a change in cyclic pitch causes the blades to flap. This factor, plus the desirability of relieving bending stresses by permitting the blades to cone, requires the use of flapping hinges.

The other possibility for full articulation lies in permitting the blades to lead and lag (hunt) in the plane of rotation. This action, of course, would require movement about a hinge with axis parallel to the main rotor shaft.

Full articulation in a rotor head permits the blades to change pitch, flap, and hunt. Basically, pitch change is the only action controlled directly by the pilot. The other two actions occur as a natural function of pitch change and forces incurred during rotor operation.

In the paragraphs to come we are going to investigate each of these blade movements with regard to the limits of action, the causes for the action, and any special considerations relative to the action.

There is little we can add to our previous discussions of blade pitch change. We have seen the necessity for it and we have learned how it is accomplished.

Figure 41 illustrates a rotor blade at zero degrees flapping and shows upward flapping or coning to the extent of about 35 degrees above the zero flap line and about 5 degrees below the line. Disregarding for the moment actual rotor operation, this simply means that the blade can physically flap upward more than 35 degrees without interference from any part of the rotor head assembly. The blade can also flap below the zero flap line approximately 5 degrees. The flapping hinge of our fully articulated rotor head thus permits some 30 to 40 degrees of blade flap without abnormal contact with a stop or other structure.

This flapping freedom is limited with the rotor at rest or slowly turning in order that gusty wind conditions cannot flap the blades excessively
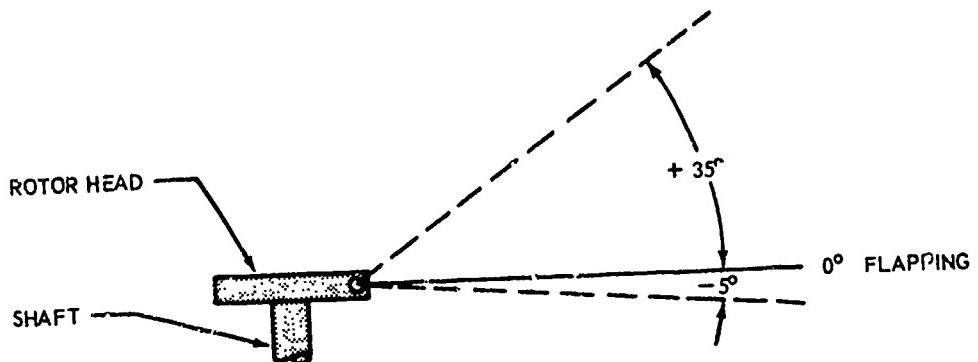
Figure 41 — Flapping limits.

and also to provide ground clearance for operating personnel or other obstructions. Droop stops, spring and centrifugally operated, prevent the blades from utilizing the 5 degrees of flapping below the zero flap line, and anti-flapping restrainers, similiarly operated, prevent the blades from moving upward in the plus range.

With regard to normal flight operation, the combination of blade weight, aerodynamic loads, and centrifugal loading, permits coning angles of about 6 degrees and flapping angles of plus or minus 6 degrees. There are, of course, maneuvers which could cause load factors sufficient to cone the rotor as much as 18 degrees with flapping angles of plus or minus 12 degrees. Needless to say, these would be out of the realm of normal flight operations. They are possible, however, without structural interference at the rotor head.

The third element of full articulation, that of movement of the blade in the plane of rotation, is called *hunting* or *leading and lagging*. The hinge which permits this movement is commonly referred to as the *drag hinge*.
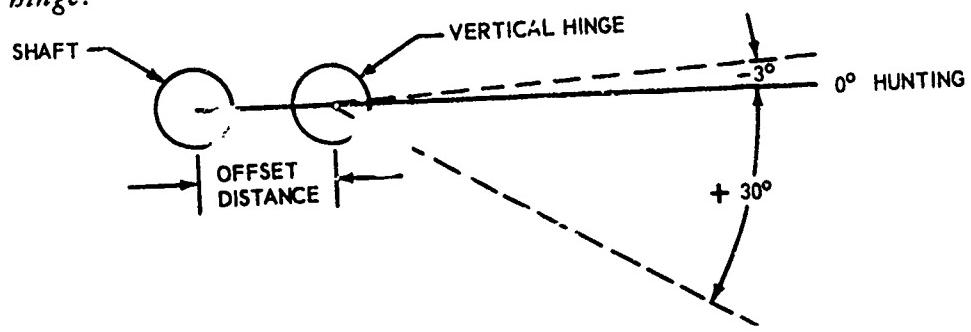

Figure 42 — Lead-lag motion limits.

Notice in Figure 42 that the blade at the zero degree hunting point forms a pure radial line from the center of the main rotor shaft through the axis of the drag hinge. While the blade may move approximately 3

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degrees forward of the radial line and about 30 degrees aft of it, further movement is prohibited by stops on the damper. A full discussion of the damper will be presented later in the text.

While it is quite easy to see why the blades must be able to change pitch and how pitch changes cause coning and flapping, it is a little more difficult to understand the reasons for permitting the blades to lead and lag. Essentially, the drag hinge is required in order that the blade may seek a position of equilibrium aft of the radial line in powered flight and along or slightly forward of the radial line in autorotation. If the ability to seek various positions were not made possible by means of the drag hinge, in-plane bending of the blade could occur. Such equilibrium is found for hovering flight by equating to zero the centrifugal and aerodynamic drag moments. The angle between the pure radial line and the spanwise axis of the blade, known as the average lag angle, is also greatly affected by the offset of the drag hinge from the center of the main rotor shaft. In forward or directional flight, other factors must also be considered. They will be discussed later in the text.

To simplify the preceding paragraph, let us assume that a heavy, flat, thin blade is rotating at constant velocity in a chamber evacuated of air. It would tend to rotate maintaining a pure radial position even though a drag hinge permitted it to hunt in the plane of rotation. If air were suddenly introduced into the chamber, the blade would experience aerodynamic drag and would assume a position somewhat aft of the radial position. Now give the blade the configuration of an airfoil and fly it with an angle of attack. Aerodynamic drag, both of the profile and induced variety, will cause the blade to lag behind the radial position even more.

Centrifugal force would have the blade fly in a pure radial position. Aerodynamic drag and hinge offset prohibit this. Because centrifugal force is caused by rotation or RPM, we may say that the average blade lag angle is determined by the relative strength of centrifugal force (RPM) and drag (power). We associate drag with torque or power because it is impossible to draw large amounts of power from an engine without loading it. The only way to substantially load a helicopter engine is to increase the pitch and/or angle of attack of the rotor blades. Increasing pitch automatically increases power through throttle synchronization on a piston engine, and through the fuel control unit in a gas turbine engine. Simply stated, average lag angle is determined by RPM and power.

In Figure 43, position "A" represents the average lag angle under a condition of high RPM and low power. The high RPM condition causes

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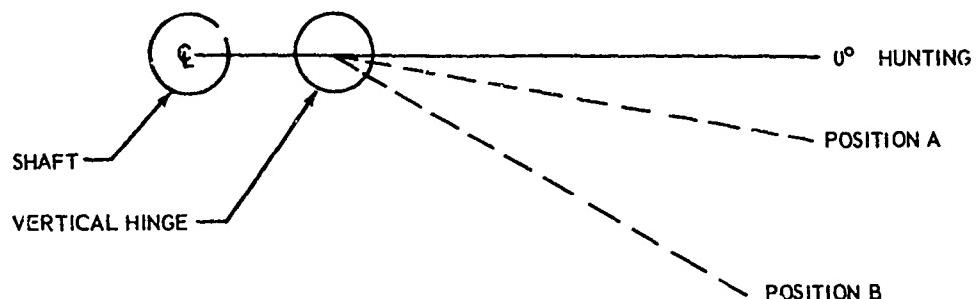
Figure 43 — Blade lag with power on.

high centrifugal loadings which tend to bring the blade closer to the radial position. The low power condition with its associated low pitch and attendant low drag also contributes to the blade's position closer to the radial line. In this condition, the average lag angle will be relatively small.

Position "B" represents the average lag angle of the blade under a condition of high power and low RPM. The lower RPM reduces centrifugal loadings and permits the higher drag, caused by increased power and its related increased pitch, to make the blade fly further aft of the radial position.

While it will be fully discussed later in the text, it should be mentioned at this time that there will be a minor leading and lagging of the blade about the average lag angle when cyclic pitch is applied to the rotor. In addition, varying air loads will also cause movement of the blade about the average lag angle.

In our discussions so far we have mentioned the fact that the rotor systems we are studying utilize fully articulated rotor heads with *offset hinges*. The term *offset* covers the fact that the blades hunt and flap from a point several inches away from the center of the main rotor shaft. Because early Sikorsky helicopters employed a flapping hinge which was located substantially at the main rotor shaft center, there are obviously good reasons why offset hinges were employed as the state of the art progressed. These will be discussed at this time.

With blades that are free to flap and hunt, and with the flapping hinge located substantially at the center of the main rotor shaft, it may be seen that pitching and rolling moments cannot be transmitted to the hub. The blades will always seek equilibrium by flapping, thus eliminating the aerodynamic moments which might pitch or roll the aircraft. This apparently rosy picture had a flaw in it, however. The fact that in early helicopters the flapping hinge was on the shaft centerline and prohibited any moments from being transmitted to the hub proved to be a problem in the long run.

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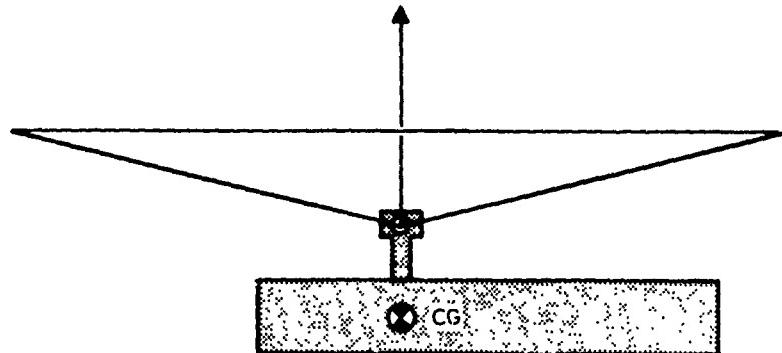
Figure 44 — Flapping hinge without offset — neutral CG.

The simple diagram in Figure 44 indicates a rotor system wherein the flapping hinges are located on the main rotor shaft centerline. The helicopter is hovering and the center of gravity is located substantially under the main rotor shaft. Because in a fully articulated rotor system *without* offset hinges, no moments can be transmitted to the hub and fuselage, tilting the rotor by cyclic pitch causes little movement of the fuselage. This is shown in Figure 45.
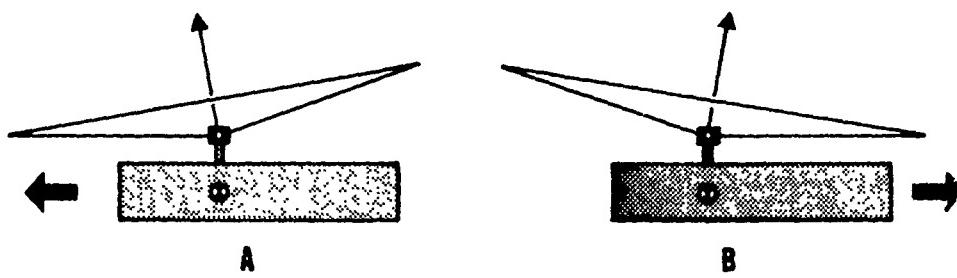

Figure 45 — Tilting rotor without offset — neutral CG.

When cyclic stick is moved forward or aft, the resulting rotor tilt produces thrust in the desired flight direction. The fuselage remains relatively level during flight until large amounts of parasite drag cause a progressively nose down condition. So long as the center of gravity remains within a relatively small range (about 3 inches), little difficulty is encountered.

In Figure 46, the center of gravity has been moved considerably aft of its normal range. When the pilot picks the helicopter up off the ground into a hover, the aircraft will immediately start to fly backward because the pilot has not applied any cyclic pitch and the rotor axis and shaft axis are along the same line with the rotor tilted aft. The dotted lines indicate this condition. The pilot, in attempting to stop his rearward flight, applies forward cyclic stick, thus bringing the tip path plane into a

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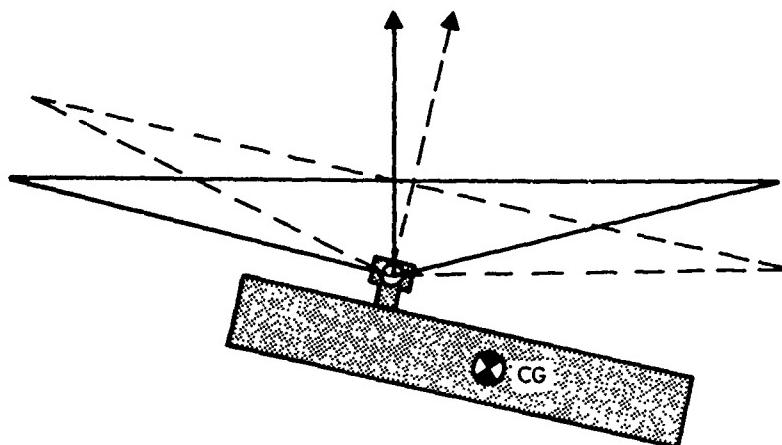
Figure 46 — Rotor without offset hinges — CG off center.

horizontal position. The solid lines indicate this condition. This action, of course, places the thrust of the rotor vertical and the helicopter then hovers over one spot on the ground. In achieving this condition, however, the pilot has utilized a good percentage of his forward cyclic stick range, thus limiting himself as to the amount of speed he can produce by further forward motion of the cyclic stick.

In order to alleviate this condition of limited center of gravity travel, as well as to produce greater overall controllability and faster control response, rotor heads were designed with a specified distance or offset between the centerline of the main rotor shaft and the flapping hinge axis. This distance can amount to from 6 inches to more than t ͻ feet. The offset is illustrated in Figure 47.
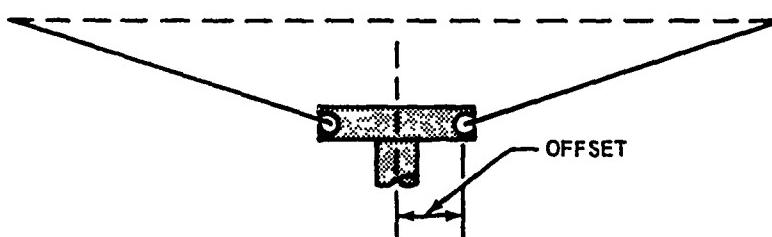
Figure 47 — Rotor with offset hinge — untilted.

To illustrate the effects of offsetting the flapping hinge from the center of rotation, the solid lines in Figure 48 show an offset hinged rotor head with blades rotating. The cyclic stick has just been pushed forward. The blades are flapping high over the tail and low over the nose, thus tilting the rotor forward. Notice that the virtual axis of the rotor has moved forward of the shaft axis. Remember, we are looking at the rotor at the
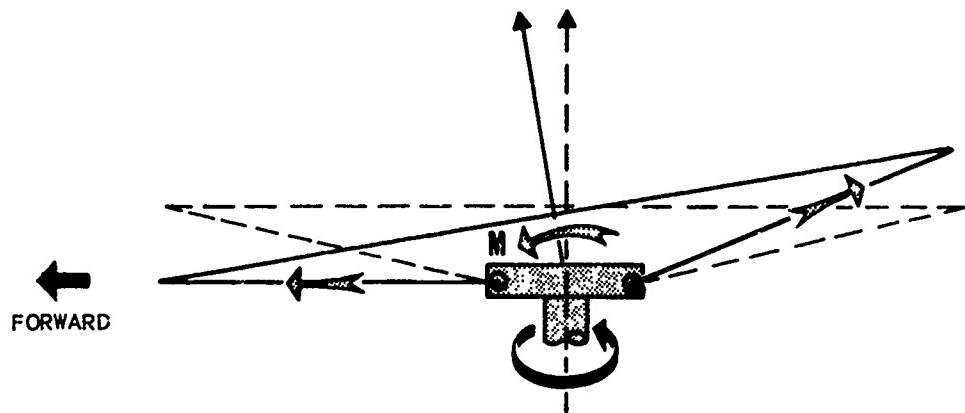
FORWARD

Figure 48 — Til'ing rotor with offset hinges.

very instant that the cyclic stick is moved forward. (The dotted lines show the rotor before cyclic stick movement in order to provide a reference position.)

It can be seen that the mass forces of the blades (centrifugal), pulling upward over the tail and downward or straight ahead over the nose, will cause a moment at the hub or rotor head. These forces and the moment direction are shown in Figure 48 as the shaded arrows. Due to the fact that there is considerable distance between the hinges of the blades, the centrifugal loading of the upflapping and downflapping blades will produce a moment which, *acting through the offset distances*, will tend to line up the plane of the rotor head with the plane of rotation.
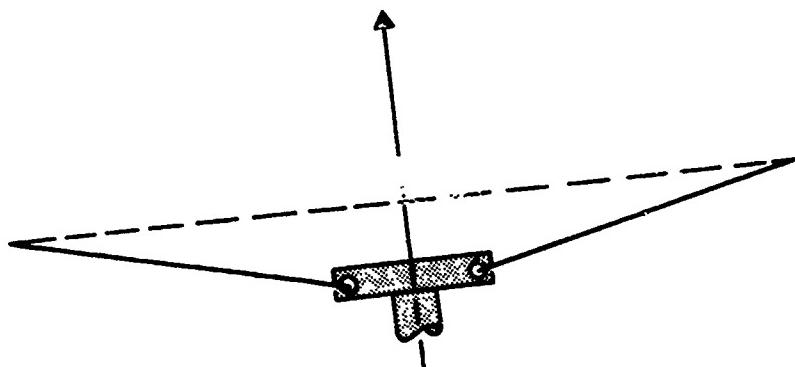

Figure 49 — Rotor with offset hinge — tilted.

Figure 49 illustrates the situation shortly following the pushing forward of the cyclic stick. The moment caused by the mass forces of the rotor blades has positioned the plane of the rotor head roughly parallel to the plane of rotation. Thus, the rotor head and the helicopter itself

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have now substantially aligned themselves with the tip path plane of the rotor. Cyclic stick has been returned to near neutral and the virtual axis of the rotor and the shaft axis are about the same.

Here we have an excellent condition for cruising flight. The rotor is tilted so as to produce directional thrust for cruising, yet we have maintained fully adequate fore and aft cyclic stick range. Under this condition, adequate amounts of controllability are available for additional forward thrust or to handle a wide spread of center of gravity conditions.

To further contribute to this cruise condition wherein no great amount of cyclic pitch is required, the main transmission is placed into the helicopter so that the main rotor shaft is inclined approximately 3 to 4 degrees forward. This means that with the helicopter fuselage level, and with no cyclic pitch applied, the rotor is already tilting 3 degrees forward. Center of gravity travel, limited to about 3 inches in the early helicopters without offset hinges, has been increased to more than 20 inches in current production helicopters.

Further along in this text, additional reference will be made to blade movements about the flapping and drag hinges. What we have discussed thus far will enable us to more fully understand the rotor's reaction to these movements.

It is basic to state that a single rotor helicopter must have some means of compensating for main rotor torque. With a main rotor rotating counterclockwise, main rotor torque will cause the nose of the helicopter to turn opposite the direction of rotor rotation, or to the right.

Figure 50 illustrates a main rotor turning counterclockwise. It shows the torque force arrow pointing opposite rotor rotation. It also shows the tail rotor with its thrust applied to the right, or in the direction of main rotor rotation and against the force created by main rotor torque. The helicopter is directionally stable because the torque compensating effect of the tail rotor has balanced main rotor torque. Naturally, main rotor torque will vary according to the power being applied to the main rotor. The more power, the more torque. The more torque, the more requirement for additional thrust by the tail rotor.

Primarily the tail rotor is a torque compensating device. Secondarily, it is the means by which we control movement of the helicopter about its vertical axis. By over-compensating for main rotor torque (left rudder), we can turn the nose of the helicopter to the left. By under-compensating for main rotor torque (right rudder), we can turn the nose of the helicopter to the right. While this method of directional control is excellent, and while the effect of main rotor torque is overcome, we pay a small
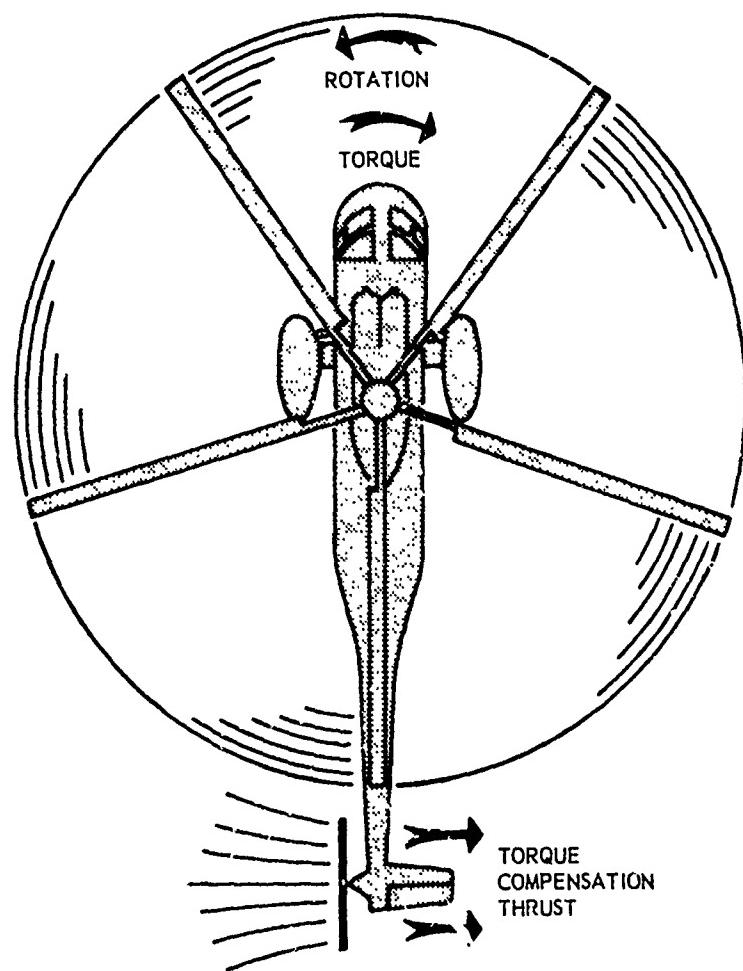
Figure 50 — Torque compensation.

penalty for the use of the tail rotor. The penalty is the requirement for power which must be borrowed from the total power available. Under varying conditions and in varying amounts the transaction reduces the power available to the main rotor. Fortunately, the power available from modern powerplants with their amazing weight-to-power ratios, tolerates this loan of power to the tail rotor with little serious effect on total aircraft performance. Although there are other methods of counteracting torque, there are penalties of weight, interference, and handling qualities without any significant benefit in total performance.

Referring to Figure 50, it may occur to the reader that although the thrust of the tail rotor is compensating for main rotor torque, it would appear that another problem may have been created by this action. The tail rotor, rotating in a vertical plane, is a thrust-producer. It produces

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thrust by accelerating a mass of air. While the primary purpose of its thrust is to compensate for main rotor torque, what is to prevent the entire helicopter from drifting to the right? After all, *it is a propeller and it is producing thrust to the right*! Actually, without correction, the helicopter *will* drift to the right.
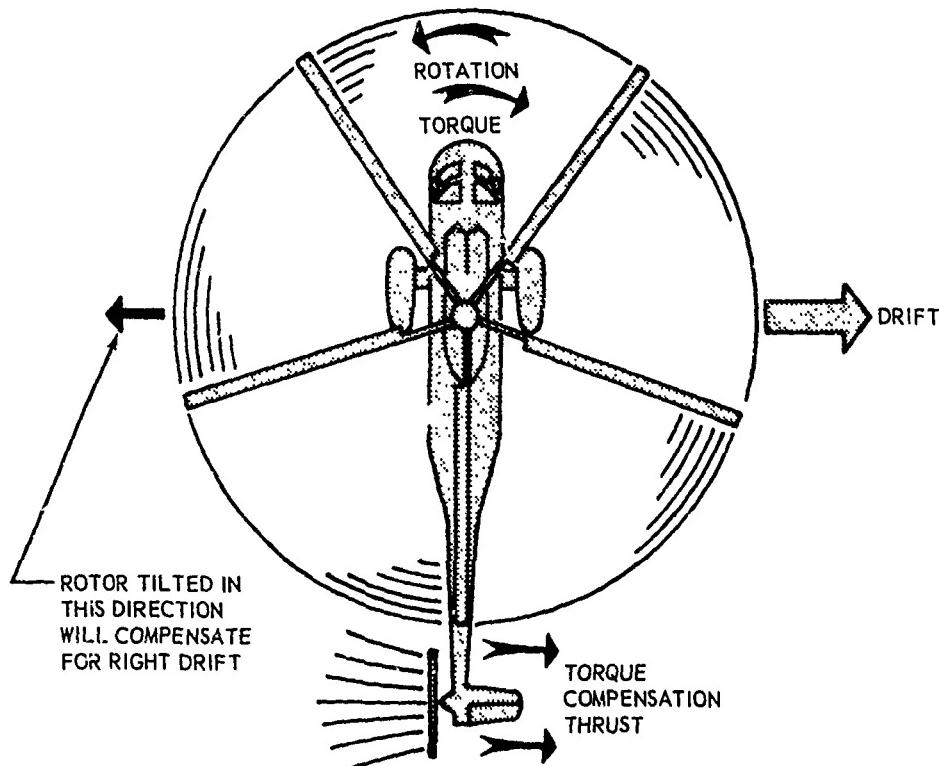
Figure 51 — Lateral drift compensation.

Figure 51 illustrates a hover condition on a no-wind day. The cyclic stick is being held neutral laterally. The main rotor is not tilted to either left or right and the control system does not incorporate *lateral lead*. Because power is being applied to the main rotor, torque is present which is being compensated for by the thrust of the tail rotor. Even though the thrust of the tail rotor is compensating for main rotor torque, that same thrust is causing the helicopter to drift to the right. This is indicated by the large arrow.

The right drift can be eliminated by tilting the main rotor slightly to the left. This is accomplished by applying a little left cyclic stick. The resulting directional thrust of the main rotor to the left compensates for the right drift. The amount of left stick necessary is barely noticeable. In some helicopters this correction is built into the control system

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tnrough what is referred to as *lateral lead*. Lateral lead means that as the collective pitch stick is raised, thus producing more power to the main rotor, the geometry of the control system is such that the right lateral servo moves upward a little more than the left lateral sei o. This slight bias causes the blades to flap up a little on the right side of the helicopter and flap down a little on the left side, thus producing a tilt to the left. Because the offset hinges cause the rotor head to assume a position roughly parallel to the plane of rotation of the main rotor, *the helicopter will hover slightly left wheel low*. The helicopter *will also hover slightly tail wheel low* because the main transmission and rotor shaft have been placed into the helicopter with a 3 to 4 degree *forward tilt* as discussed earlier in this chapter. With cyclic stick held in neutral longitudinally, the helicopter will move slowly forward because of the built-in forward rotor tilt. A little aft cyclic stick corrects the forward movement, but causes a slight tail low attitude in the hover.

From the above it may be seen that hovering with left wheel and tail wheel low is normal to the single rotor helicopter incorporating offset hinges and built-in forward transmission tilt. It is interesting to note that in the Flying Crane configuration which spends most of its time picking up and depositing loads on the ground, the main transmission has a built-in tilt *both forward and to the left*. The resulting rotor tilt forward and to the left produces wheels-level take off and landing attitudes with normal loadings.

Chapter 4

VELOCITIES, ROTATIONAL AND OTHERWISE
WITH INTRODUCTION TO BLADE TIP STALL

While the helicopter itself does not require airspeed in order to become and remain airborne, its rotor blades must have sufficient air flowing over and under them to produce lift. The required airspeed is produced by rotating the blades through the air. While this fact is elementary, some rather surprising problems crop up during the production of the required lift.
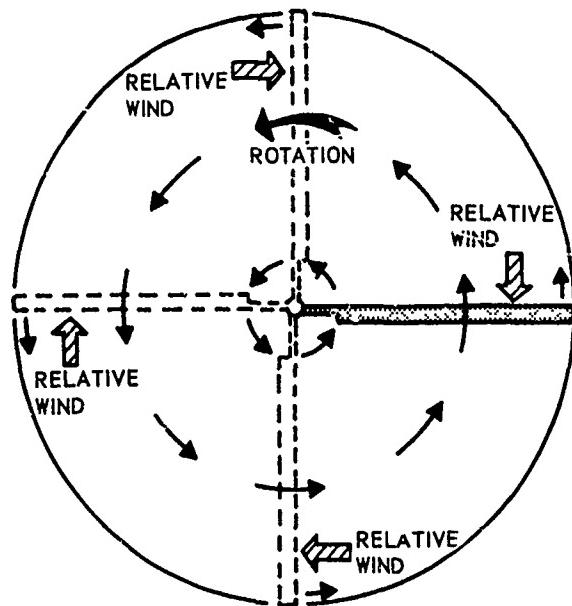
Figure 52 — Rotor velocity — hovering.

In Figure 52 we see a rotor disk with a blade extending from the center of the main rotor shaft. The rotor is turning at 200 RPM. At the center of the main rotor shaft the rotational velocity is microscopic. At the inboard pocket of the rotor blade, the distance through space travelled by that pocket is relatively small. Consequently its rotational velocity is not too significant. Remember that in the rotor hovering or rotating on a no-wind day, rotational velocity means airspeed. Thus, the inboard pocket of the blade has but little airspeed. The middle pocket of the blade, however, has a much greater distance to travel through space in one revolution of the rotor. Its rotational velocity airspeed is considerably greater. The tip of the blade must travel the entire circumference of the rotor disk in one revolution. Its rotational velocity and airspeed are the maximums produced by the RPM and diameter of the rotor. Despite the many problems encountered by

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utilizing airspeed resulting from rotational velocities, one fact may be noted; *the relative wind flows substantially at right angles to the leading edge of the blade regardless of its radial position.* The relative wind created by high speed directional flight changes its perpendicularity only slightly. This slight change is illustrated in Figure 53.

FLIGHT DIRECTION

RRW

D

R

ROTATION

RRW

D

R

R = ROTATIONAL RELATIVE WIND

D = AIRCRAFT FLIGHT VELOCITY
    RELATIVE WIND

RRW = RESULTANT RELATIVE WIND
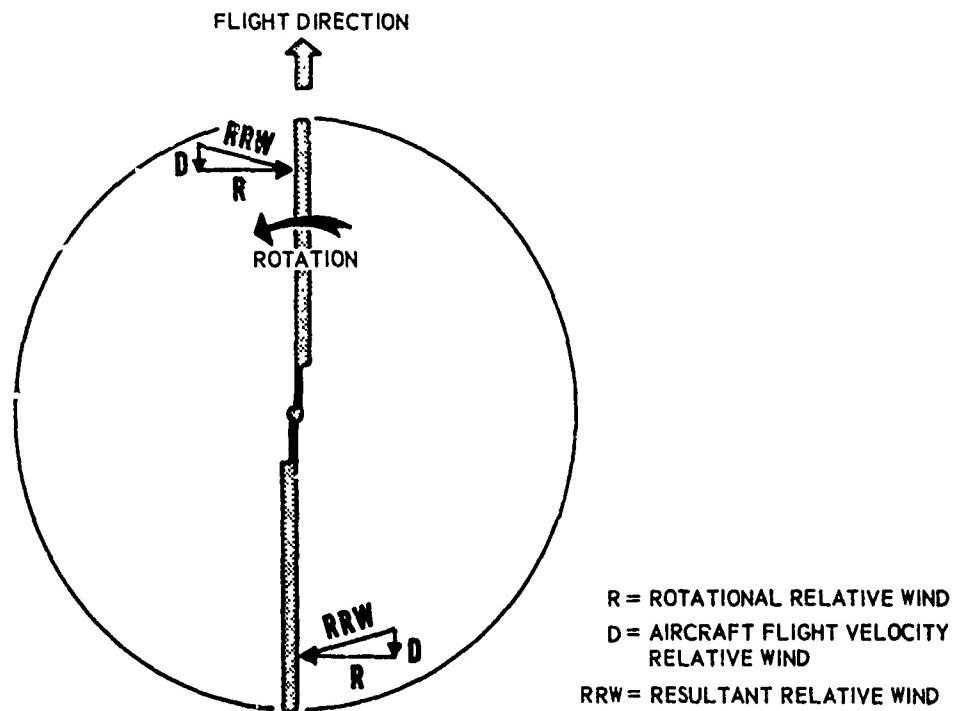
Figure 53 — Relative wind perpendicularity.

In Figure 53 the blade over the nose of the helicopter has an effective relative wind which is the resultant of the rotational velocity relative wind and the aircraft's directional velocity relative wind. Notice that the direction of the resultant relative wind is not too far removed from perpendicularity. The same may be said for the blade passing over the tail cone or aft portion of the fuselage. It may also be seen that while the resultant relative wind may be a few degrees off perpendicularity, the actual airspeed value will be little affected.

With reference to rotational velocities and their associated airspeeds, it is well to have a reference point in mind. Because the tip of the blade is subject to the maximum velocities, we will utilize that location as a reference.

We have stated that the center of the main rotor shaft has negligible rotational velocity and that the rotational velocity for each section of the blade varies according to its radius or distance from the center of the main

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rotor shaft. Let us see what sort of velocities are encountered at the tip of the blade.

One of our late generation helicopters has a *tip velocity* of 658.7 feet per second at normal rotor RPM. In autorotation the velocity increases to 769 feet per second. In terms of miles per hour this amounts to 449 miles per hour at normal RPM and 524 miles per hour in autorotation. For the sake of a standard reference, let us utilize a reference tip speed of 500 miles per hour.

When we consider that we are asking the rotor blade to perform efficiently with a near-zero airspeed at the root of the blade and 500 miles per hour at the tip, we are not wrong in assuming that we will encounter a few problems.

This extreme airspeed differential is, of course, caused by the fact that the airspeed is derived from rotational velocity. The lift or thrust of the blade increases toward the tip due to the increased rotational velocity airspeed. This increase in lift does not vary with the radius, but with the *radius squared*. Stated another way, lift varies as the square of the speed.

Because induced drag, like lift, varies as the square of the speed, large amounts of induced drag will be experienced near the tips of the blades. Profile drag, varying as the *cube* of the speed, makes drag losses increasingly serious. While reduction of tip speed would alleviate this condition, this expedient is not available because the rotor has been designed to perform in conformance with selected criteria utilizing a specified rotor diameter and operating at a particular RPM.

It would seem that profile drag losses and that portion of the total induced drag loss caused by non-uniformity of inflow could be reduced by tapering the blade (old method) so that the chord at the blade root is greater than the chord at the tip. The same result could be achieved by twisting the blade (current method) so that higher pitch angles exist at the root of the blade than at the tip. Either of these methods is logical because profile drag losses vary as the cube of the velocity while thrust (lift) and its attendant induced drag vary as the square of the velocity. Quite obviously it is beneficial for thrust (lift) to be produced by the low airspeed part of the blade near the root, while keeping low angles of attack near the blade tip. Blade twist, among other benefits, increases both the induced velocity (accelerated air) and the blade loading near the inboard section of the blade.

The curved line in Figure 54 illustrates the lift distribution of a constant chord, untapered, untwisted rotor blade with zero airspeed at its root and 500 miles per hour at its tip. The curved line, of course, denotes non-

50
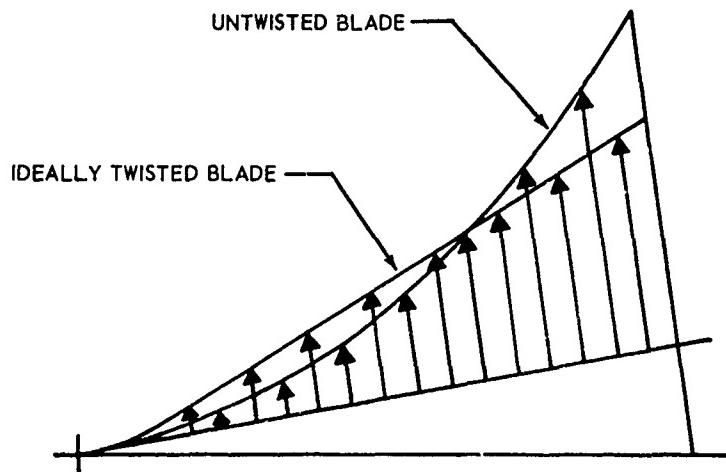
Figure 54 — Blade loading — twisted versus untwisted.

uniform lift distribution. The straight line in the same illustration indicates the lift distribution of an ideally twisted blade. It denotes uniform lift distribution.

To sum up, in an untwisted blade the inflow varies almost linearly with the radius. In an ideally twisted blade the inflow is substantially constant along the radius. The lift of an untwisted blade varies as the radius squared. In an ideally twisted blade the lift varies with the radius.

Physically, blade twist means just what the name implies. The blade spar, prior to the pocket attachment process and before any real surface finishing is accomplished, is placed in a fixture which holds one end of it securely fastened. Another machine, operating on tracks, produces a torsion or twisting of the spar at specific intervals as it moves toward the opposite end of the blade. By the time the operation is completed, the blade has been twisted about 8 degrees negatively. This would correspond to *"washout"* on a fixed wing aircraft. As an illustration of what has taken place, if the chord of the root end of the spar were held 8 degrees above horizontal, the tip of the spar would be horizontal.

Figure 55 shows how both the induced velocity and the thrust or blade loading can be increased toward the root of the blade. While the drawing illustrates conditions implying "ideal twist" (a theoretical perfect twist disregarding certain factors including the fact that uniform inflow distribution requires a different twist distribution for each thrust coefficient or climb rate), it is nevertheless sufficient to illustrate the point.

Drawing (A) of Figure 55 shows an outboard airfoil section near the tip of the blade. The horizontal arrow indicates the direction and high velocity of rotation and the magnitude and direction of the relative wind. The small

51

PITCH ANGLE

ANGLE OF ATTACK

ROTATION

INFLOW VELOCITY

RESULTANT RELATIVE WIND (FLIGHT PATH)

ROTATIONAL RELATIVE WIND

A

(OUTBOARD)

PITCH ANGLE

ANGLE OF ATTACK

ROTATION

INFLOW VELOCITY

RESULTANT RELATIVE WIND (FLIGHT PATH)

ROTATIONAL RELATIVE WIND

B

(INBOARD)
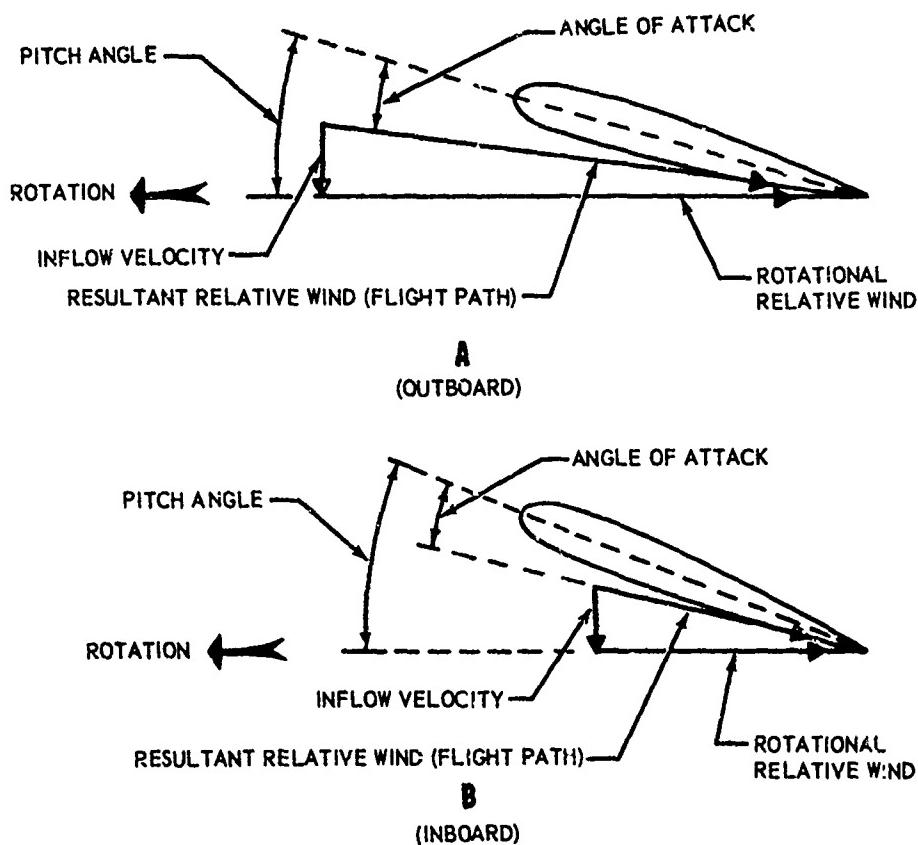
Figure 55 — Blade section angle of attack — twisted blade.

vertical arrow indicates the direction and value of the inflow wind as described in the first chapter on basic aerodynamics, Figure 4. Naturally, when winds from two directions are acting on the blade, the actual relative wind will be the resultant of the two. The resultant relative wind is so indicated in the drawing. Notice that the angle of attack is much less than the actual pitch angle of the blade.

Drawing (B) of Figure 55 shows an inboard airfoil section near the root of the blade. Notice that the value of the inflow has been kept constant and that the pitch of the blade varies inversely with the radius in order to maintain a positive angle of attack.

While much of our discussion on negative blade twist pertained to hovering flight, its benefits also extend to forward flight in the form of better rotor efficiency. Because the rotor blade tips operate at lower angles of attack, this area is unloaded sufficiently to postpone the onslaught of blade tip stall. Losses due to compressibility are also reduced because reduced lift coefficients cause the critical Mach number of the blade to increase.

52

In this chapter we have concerned ourselves only with the *basic* problems of utilizing rotational velocity relative winds and airspeeds. By understanding these problems and correcting for those factors for which correction is possible, we have seen that the helicopter can become airborne in the hover condition without too much loss of efficiency.
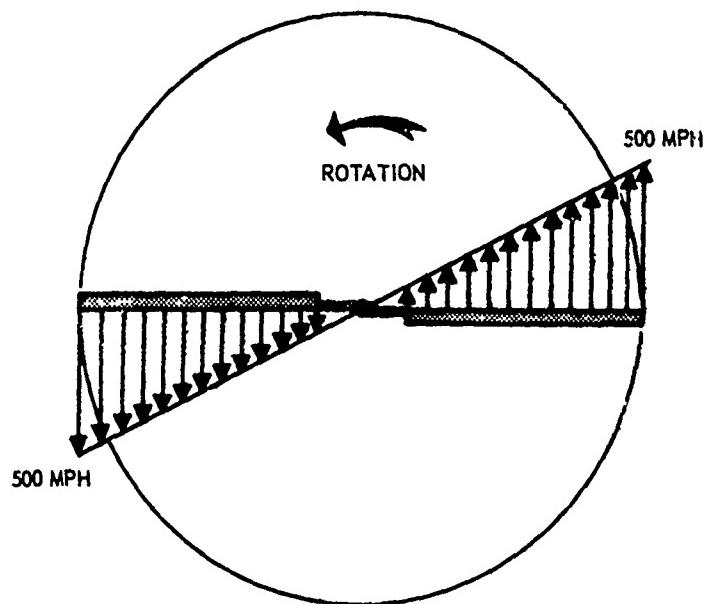

Figure 56 — Velocity distribution — hovering.

As may be seen in Figure 56, the establishment of the rotational airspeed value for any section of the blade may be computed by simple measurement. If the arrow at the tip of the blade indicates 500 miles per hour and the main rotor shaft centerline indicates zero miles per hour, the airspeed of any radial point along the blade span can be determined by the use of a ruler with appropriate increments.

As might be suspected, however, the situation changes with the introduction of forward flight by the helicopter. Any object passing through the air will create a relative wind which flows opposite the object's flight path. The speed with which the object passes through the air is its airspeed. In the case of the helicopter, forward flight creates a new relative wind which has an effect upon the one created by rotation. Rotational relative winds affect only the rotor blades when the helicopter is hovering. The relative wind created by forward flight of the helicopter affects not only the rotor blades but the entire helicopter. Quite naturally, rotor blade airspeeds will be affected.
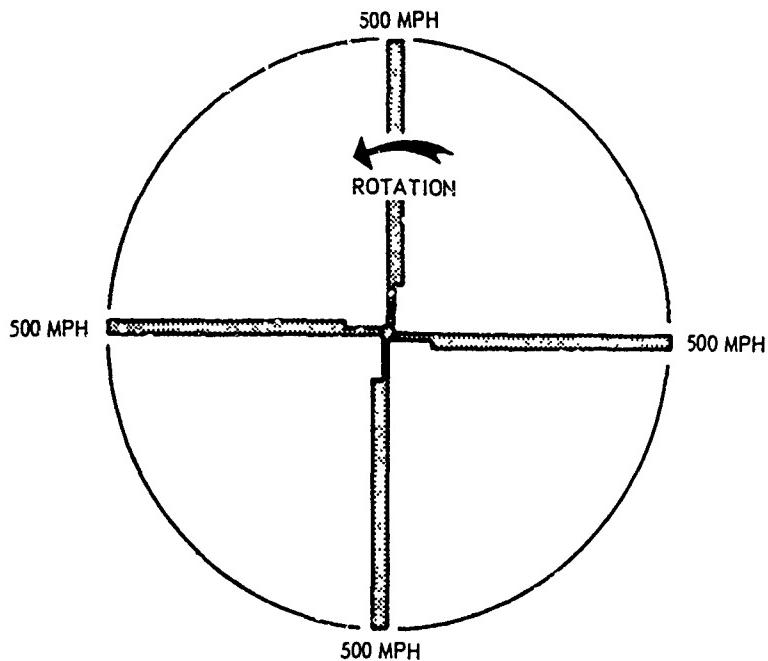
Figure 57 — Tip speed — hovering.

Figure 57 illustrates a fouɪ ɔlade rotor system rotating counterclockwise. Note that the rotor is turning and that the tip velocity is 500 miles per hour regardless of radial position. It goes almost without saying that tip airspeed is also 500 miles per hour. The helicopter is hovering and there is no surface wind blowing.

From this flight condition, we are now going to move forward into directional flight. We are going to establish an aircraft airspeed of 100 miles per hour. This means that a 100 mile per hour relative wind will be flowing past the helicopter.

Figure 58 illustrates the rotor moving forward at a speed of 100 miles per hour. It shows a 100 mile per hour relative wind flowing into the rotor. As stated before, the addition of this new relative wind value will veɪy definitely affect the rotor blades and their airspeeds.

Notice that over the right side of the helicopter the rotor blade has a 500 mile per houɪ airspeed which is caused by its rotational velocity at that point. In addition, the aircraft's forward velocity relative wind is flowing over the blade at that point. This relative wind has a value of 100 miles per hour. The air flowing over the blade at that point is thus travelling at 600 miles per hour. Over the nose and the tail of the helicopter, the blade's airspeed has returned to approximately 500 miles per hour. The effect of the 100 mile per hour aircraft relative wind over the nose and tail is minor

FORWARD FLIGHT
AT 100 MPH

AIRCRAFT
RELATIVE WIND
100 MPH

AIRCRAFT
RELATIVE WIND
100 MPH

ROTATION

ROTATIONAL AIRSPEED	500 MPH		500 MPH	ROTATIONAL AIRSPEED
AIRCRAFT AIRSPEED	−100 MPH		+100 MPH	AIRCRAFT AIRSPEED
TOTAL BLADE AIRSPEED	400 MPH		600 MPH	TOTAL BLADE AIRSPEED
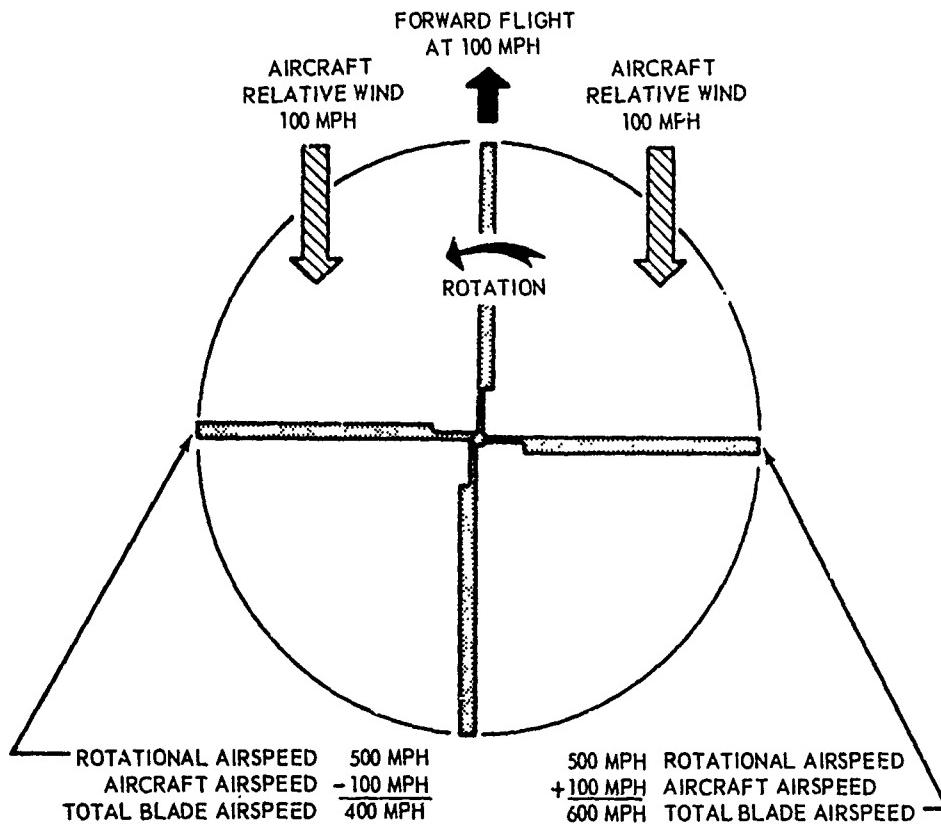
Figure 58 — Tip velocity in forward flight.

and results only in a slight change in the direction of the relative wind with regard to the leading edge of the blade. This slight change was illustrated in Figure 53.

On the left side of the helicopter the rotor blade has a 500 mile per hour rotational velocity. The 500 mile per hour airspeed that this rotational velocity would normally produce has been modified, however, by the fact that the aircraft relative wind, flowing at 100 miles per hour, *is flowing in the same direction that the blade is moving*. The 100 mile per hour aircraft airspeed must therefore be subtracted from the normal 500 mile per hour rotational velocity airspeed. This leaves a total blade airspeed of only 400 miles per hour over the left side of the helicopter.

It should be noted at this time that the blade travelling from the tail to the nose around the right side of the helicopter is termed the *advancing blade*. It is *advancing into* the aircraft relative wind. The blade travelling from the nose to the tail around the left side of the helicopter is called the *retreating blade* because it is moving or *retreating with* the aircraft relative wind.

Forward flight at 100 miles per hour has thus created an airspeed differential of 200 miles per hour between the tip of the blade on the right (advancing) side of the helicopter and the tip of the blade on the left (retreating) side of the helicopter. Because lift or thrust varies as the square of the velocity, the variation or *dissymetry of lift* between the two sides of the rotor disk becomes a serious problem.

Dissymetry of lift is not a phenomenon associated solely with the helicopter. Practical development of the autogyro began in 1920 and the information gleaned from the process proved invaluable to those interested in designing a successful helicopter. Any mention of the autogyro must, of course, recall the name Juan de la Cierva. He flew his first autogyro in 1923 and built three of them before producing a truly successful one. Discovering that a rotor tilted slightly back in the wind and with blades operating at low positive angles could produce sizeable amounts of lift even at very low speeds, his machine's rotor turned in *autorotation* as the aircraft was pulled through the air by a conventional engine and propeller. By 1935 such factors as gearing the engine to the rotor to bring it up to speed, tilting the rotor axis by direct action of the pilot controls, and the *jump takeoff* made possibly by overspeeding the rotor on the ground and then applying pitch rapidly, made the autogyro a close cousin of the helicopter with regard to flight characteristics.

Cierva's early autogyros utilized rigid rotors. The blades were not free to flap. It follows that as the autogyro was pulled through the air or across the ground by its engine and propeller and with its rotor turning in autorotation, the dissymetry of lift caused by the machine's forward velocity airspeed produced a strong rolling moment. It was like trying to fly a fixed wing aircraft without aileron control and with a high angle of incidence built into one wing and a negative angle of incidence built into the other. This rolling moment is illustrated in Figure 59.


ROLLING MOMENT

RETREATING BLADE ——— ——— ADVANCING BLADE
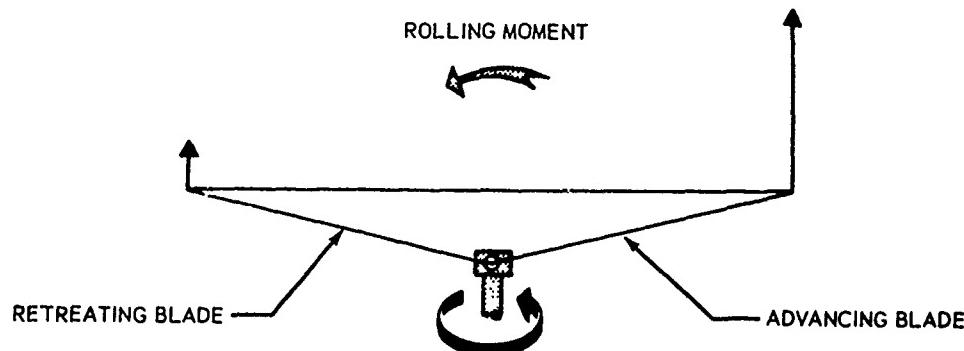
Figure 59 — Rigid rotor rolling moment in forward flight.

Cierva answered the dissymetry of lift problem in his autogyro by placing flapping hinges at the root of his rotor blades. While the flapping hinge principle was not new, having been put forth by a Frenchman named Renard in 1904, Cierva refined the idea and applied it to his autogyro.

Before analysis of how the flapping hinge eliminates dissymetry of lift, let us restate the problem. Dissymetry of lift is caused by the fact that in forward flight the aircraft relative wind is additive to the rotational relative wind on the advancing blade and subtractive on the retreating blade. The blade leaving the tail and advancing around the right side of the helicopter receives a progressively increasing amount of airspeed which reaches its maximum value directly over the right side of the helicopter and then reduces to substantially normal rotational velocity airspeed over the nose of the aircraft. Leaving the nose of the aircraft, the blade experiences a progressively decreasing amount of airspeed which reaches its lowest value over the left side of the aircraft and then increases to normal rotational velocity airspeed over the tail of the aircraft. In a rigid rotor without hinges or cyclic pitch, this dissymetry causes a rolling moment to the left.

With hinged rotor blades, the picture changes. As the blade leaves the tail and advances around the right side of the helicopter, it responds to the progressively increasing airspeed by producing more lift and climbing (flapping) upward. In flapping (climbing) upward, however, the change in blade motion or flight path causes a change in the relative wind which decreases the angle of a'   nd thus the lift. The upward flapping veloc-ity, in order that no unh   ed forces may exist in the blade, must be of sufficient magnitude so a   *decrease the angle of attack enough to keep the lift constant*. Essentially then, the extra lift and rolling moment that would have been produced by the additional airspeed on the advancing side of the rotor never materializes. Instead the blade attains its highest flapping position over the nose, and its lowest flapping position over the tail. A nose-up pitching moment results which can be overcome by cyclic pitch control. This will be discussed at the end of this chapter.

Figure 60 (A) illustrates a blade section with regard to flight path, angle of attack, and relative wind as it passes over both the nose and the tail of the helicopter (for the sake of simplicity, inflow has not been plotted). At these points its airspeed is substantially a derivative of rotational velocity. Figure 60 (B) shows that the increased airspeed on the right (advancing) side of the rotor has caused the blade to flap or climb upward. Because rela-tive wind always flows opposite the flight path and because angle of attack is the angle between the relative wind and the blade chord, it is seen that the angle of attack has been reduced. The reduction of angle of attack and

ROTATION ← ― ― ―

ANGLE OF ATTACK

FLIGHT PATH
(RELATIVE WIND)

ANGLE OF ATTACK AND FLIGHT PATH/RELATIVE WIND
OVER NOSE AND TAIL

A

RESULTANT
RELATIVE WIND

ANGLE OF ATTACK

FLIGHT PATH
(RELATIVE WIND)

ROTATION ←

UPWARD FLAPPING VELOCITY

ANGLE OF ATTACK AND FLIGHT PATH/RELATIVE WIND
OVER RIGHT (ADVANCING) SIDE

B

Figure 60 — Angle of attack and flight path changes — advancing blade.
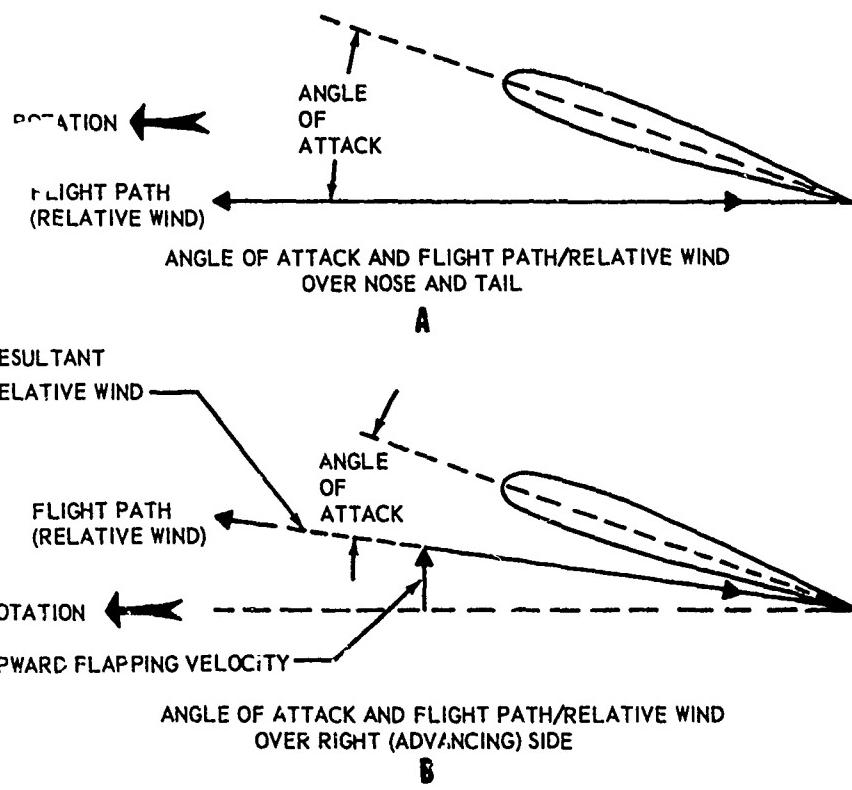
its attendant cancellation of the excess lift occur as one action thus keeping the lift constant.

As the blade leaves the nose of the helicopter and retreats around the left side, it responds to the progressively decreasing airspeed by producing less lift and diving (flapping) downward. In flapping (diving) downward, however, the change in flight path causes a change in the relative wind which increases the angle of attack and thus the lift. The downward flapping velocity, in order that the blade may remain in equilibrium, must be of sufficient magnitude so as to *increase the angle of attack enough to keep the lift constant.*

Figure 61 (A) shows the flight path, relative wind, and angle of attack of the blade as it passes over the nose and the tail. Its airspeed is substantially derived from rotational velocity. Figure 61 (B) shows that the decreased airspeed on the left (retreating) side of the rotor has caused the blade to flap or dive downward due to the loss of lift. Remembering that relative wind blows opposite the flight path, it is seen that the diving flight path has caused an increase in the angle of attack. The increase of angle of attack and its attendant build-up of the lift-loss occur as one action, thus keeping the lift constant.

58

ANGLE OF ATTACK AND FLIGHT PATH/RELATIVE WIND
OVER NOSE AND TAIL

A

ANGLE OF ATTACK AND FLIGHT PATH/RELATIVE WIND
OVER LEFT (RETREATING) SIDE

B
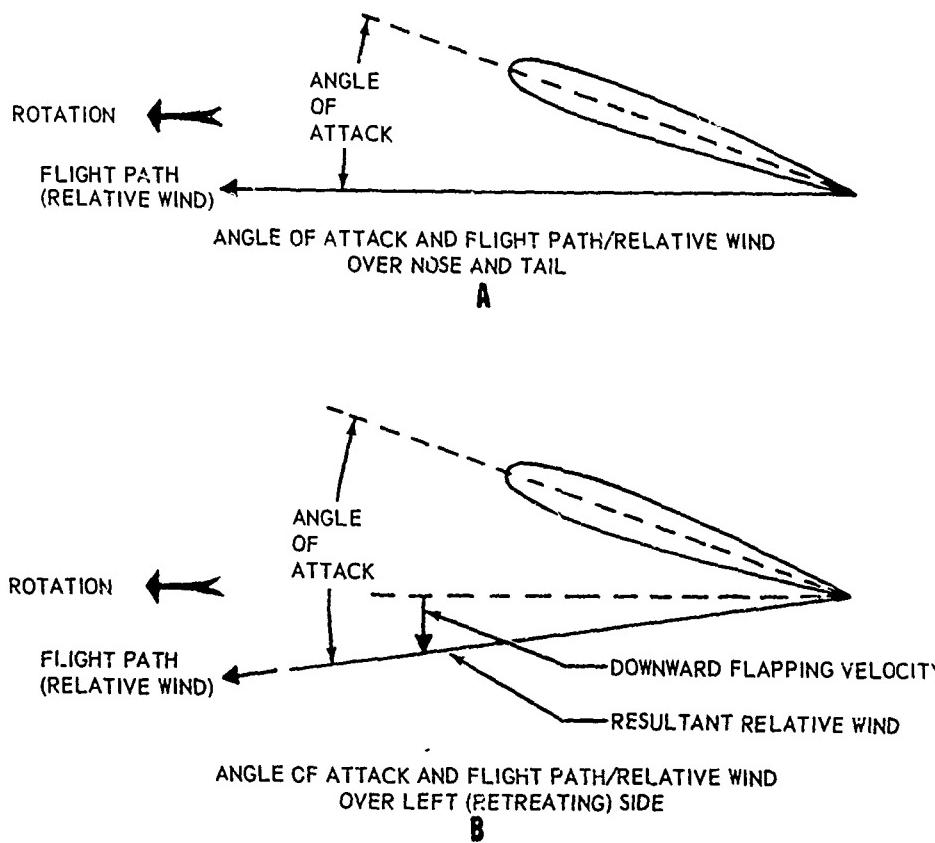
Figure 61 — Angle of attack and flight path changes — retreating blade.

It is also true that the blades may be cyclically feathered, decreasing the pitch on the advancing side and increasing the pitch on the retreating side, in order to equalize the lift on both sides of the rotor disk. In order to produce the forward speed which causes dissymetry of lift in the first place, the cyclic stick must be moved forward in order to tilt the rotor. Forward cyclic stick causes a lower angle on the advancing side and a higher angle on the retreating side. These angles work toward the equalization of lift around the disk. It may be said then that both cyclic pitch and flapping hinges work together in the elimination of dissymetry of lift. It is interesting to remember, however, that the flapping hinge is the basic weapon. After all, the autogyro had fixed-pitch blades in most cases, and the helicopter with offset hinges and built-in shaft tilt can, under ideal center of gravity conditions, fly with little cyclic pitch. Under these conditions, blade flapping is predomin; .'v eliminating the lift dissymetry.

The tail rotor, subject to the same problem but with no ability to cyclically feather its blades, must rely solely on its flapping hinge applica-
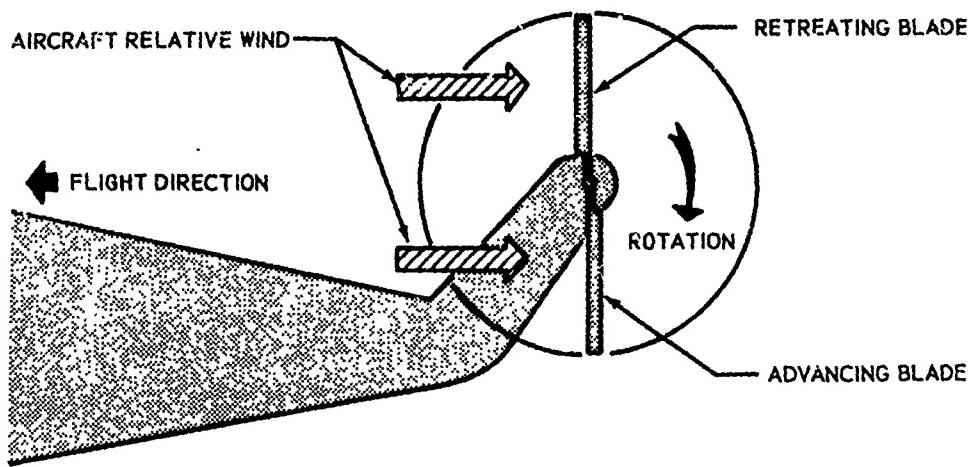
Figure 62 — Tail rotor.

tion for equalizing the thrust dissymetry. As is shown in Figure 62, the tail rotor, even though it is rotating in a vertical plane, has an advancing and a retreating blade when the helicopter is in forward flight. Rotational velocity airspeeds are increased or decreased just as they are in the main rotor and cause the same results.

Thrust dissymetry is generally eliminated in two-bladed tail rotors by utilization of a semi-rigid seesaw rotor hub with the hinge sometimes inclined from the blade feathering axis about 30 degrees. When the advancing blade flaps outward in response to the additional airspeed, the flapping causes a small change in the direction of the relative wind which tends to equalize the thrust. It is aided, however, by the fact that as the blade flaps in the direction of its thrust, the 30 degree hinge mechanically forces a pitch change to a lower value. Naturally, the retreating blade is undergoing a pitch change to a higher value to compensate for the thrust lost by the reduced airspeed.

In four-bladed tail rotor configurations the same results are obtained by the utilization of a delta hinge. There is no actual inclination to the blade hinge. The delta configuration is formed by the linkage between the pitch control beam and the bracket on the blade sleeve, and imaginary lines drawn between each end of the pitch change link and the pitch change axis of the blade. For a given rudder pedal setting, the pitch control link holds the point at which the link attaches to the blade bracket fixed. Because this point is held firm, blade flap causes an attendant change in blade pitch. This is difficult to portray graphically. The next time you are close to a non-rotating tail rotor, move a blade in its flapping direction and notice the pitch change taking place.

60

Let us now have a look at main rotor blade airspeeds during forward flight.

FORWARD
FLIGHT

AIRCRAFT
RELATIVE WIND
100 MPH

AIRCRAFT
RELATIVE WIND
100 MPH

0 MPH
BLADE
AIRSPEED
HERE

ROTATION

AIRCRAFT
AIRSPEED
100 MPH

ROTATIONAL
VELOCITY
AIRSPEED
500 MPH

TOTAL
BLADE
AIRSPEED

500
+100
600 MPH

DOTTED LINES AND ARROWS
INDICATE ROTATIONAL
VELOCITY

SOLID LINES AND ARROWS
INDICATE ACTUAL
BLADE SPEED

REVERSE FLOW AREA

100 MPH BLADE ROTATIONAL
VELOCITY HERE

500 MPH   ROTATIONAL VELOCITY AIRSPEED
-100 MPH AIRCRAFT VELOCITY AIRSPEED (TRAVELING WITH BLADE)
400 MPH   ACTUAL BLADE AIRSPEED

Figure 63 — Main rotor in forward flight.

Figure 63 illustrates a rotor in forward flight at 100 miles an hour. Blade tip rotational velocity is 500 miles an hour. Advancing blade tip airspeed is 600 miles an hour, the additive effect of rotational airspeed plus aircraft airspeed. Retreating blade tip airspeed is 400 miles an hour, the subtractive effect of rotational airspeed minus aircraft airspeed. The interesting factor here is that while the main rotor shaft has no rotational velocity at its center, it does have airspeed. It is moving through the air at 100 miles an hour with the rest of the helicopter. Notice that the arrows which indicate total airspeed show that the main rotor shaft has 100 miles an hour airspeed and that in the area of the small circle, the air is actually blowing over the retreating blade *from trailing edge to*

leading edge or, to state it another way, *backwards*! It can further be seen that there is a point at the root of the retreating blade where the airspeed is actually zero miles per hour. At this point or radial position, the rotational velocity is 100 miles per hour. The airspeed at that point is zero, however, because the aircraft velocity relative wind, travelling at 100 miles an hour in the same direction the blade is travelling, cancels out the airspeed that would have been created by the rotational velocity at that point. From that point outboard, airspeed begins to pick up again, but ends up at the tip with a value of only 400 miles an hour.

It follows that with a substantially constant rotor RPM, the greater the helicopter forward speed, the greater the advancing blade airspeed and the lesser the retreating blade airspeed. At 200 miles an hour, the helicopter's advancing blade tip is approaching 700 miles an hour airspeed, while the retreating blade's tip airspeed has been reduced to only 300 miles an hour. The critical Mach number of the advancing blade now becomes a problem, and the stalling out of the retreating blade tip poses an additional problem. Compressibility and blade tip stall thus present the ultimate challange in the performance of the true helicopter. While critical Mach values and drag divergence are not to be overlooked, blade tip stall is probably the more important stumbling block in the way of performance progress. Let us have a little closer look at this phenomenon.

Its proper name is *blade tip stall*. It is so called because the stall begins at the tip of the blade and works progressively inboard as the conditions which cause it increase in severity. It has no relationship to the obviously stalled-out area near the center of the rotor. While we know that area is present, it does not manifest itself as a vibration or result in deteriorating aircraft performance. Blade tip stall, on the other hand, very definitely affects performance as well as producing vibrations, deteriorating controllability, and, if encouraged, an uncontrolled pitch-up.

An airfoil stalls because of the following general factors:

     1. Insufficient airspeed

     2. Angle of attack too great

     3. Wing (blade) loading too great for given airspeed

It is interesting to consider that in a conventional aircraft, low speed performance is limited by the stall of its wings. In a helicopter, the reverse is true. The helicopter's high speed potential is limited. As the helicopter moves forward with increasing airspeed, its retreating blade encounters slower and slower airspeeds. In order to continue to produce its portion of the lift required, greater angles of attack are required. It

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follows that at some forward speed, the retreating blade will stall. Because in forward flight the angle of attack along the span of a blade cannot be uniform, we would logically expect that some portion of the blade will stall out before the rest. We would expect to find the stall area at that point where the greatest angle of attack exists. Let's try to find that point!
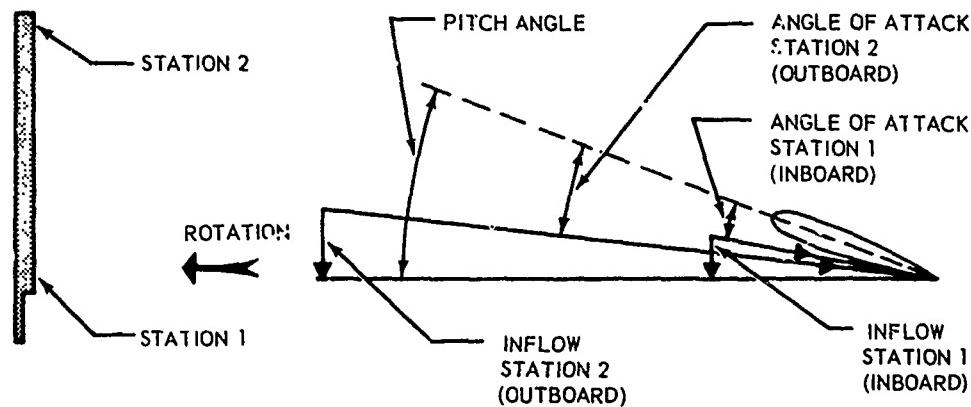

Figure 64 — Angle of attack — blade root versus blade tip.

Notice in Figure 64 that the inflow through the rotor at Station 1 where the rotational velocity is low (inboard) causes the angle of attack to become smaller than the pitch angle. This, of course, is because the rotational relative wind, flowing substantially horizontally, is joined by the inflow relative wind flowing substantially vertically, thus causing a resultant relative wind. Because angle of attack is the angle between the chord of the airfoil and the relative wind, it is easily seen that the new resultant relative wind causes the angle of attack to be less than the pitch angle.

At Station 2, however, our given inflow velocity is not as successful in reducing the angle of attack as it was at the inboard or root end of the blade. The increased tangential or rotational velocity at the tip affects the resultant relative wind so as to *increase* the angle of attack at that point. Notice that even though the inflow velocity remains substantially the same, the angle of attack has increased. If the angle of attack increases toward the tips of the blades, it can be seen that the blade load shifts toward the tips as conditions cause an increased inflow through the rotor.

Although we have not yet discussed power requirements in detail, it may be stated here that the inflow through a rotor disc varies with the power required. This will be explained in detail later in the text. For the moment, let us just state that in hovering, where considerable power is

required to accelerate the air down through the rotor, the inflow is large and the load is toward the tips of the blades. The highest angles of attack also are located at the tips of the blades, as we saw in Figure 64. In the hover, however, this is not necessarily important — at least not in a consideration of blade stall.

As we move ahead with forward speed, the rotor encounters a larger mass of air to which, per unit of time, it does not have to impart the velocity that was required in the hover. The induced flow, and consequently the entire rotor inflow, decreases and the load moves more inboard on the blades.

At high speeds, the rotor must tilt forward in order to overcome the high drag incurred. The relative wind created by the aircraft's fast directional flight acts through the tilted rotor bringing about an increase in inflow and an attendant requirement for more power.

Let us repeat that the angle of attack distribution along the span of a blade depends largely on the speed and direction of the rotor inflow. As inflow increases, the angle of attack at the tip of the blade increases with respect to the angle of attack at the root. It is not difficult to see that as our helicopter flies faster and faster, both the load and the angle of attack are rapidly increasing at the tip of the blade. Naturally there will be a point at which the blade will encounter a stall condition.

A logical question at this time would be "what effect does blade twist have upon blade tip stall?"

A blade with negative twist (lower pitch at the tip than at the root) will have a more even lift distribution along its span and will not have the excessively high angles of attack at the tip. For normal amounts of twist, however, *the highest angles still occur at the tip of the blade*! It is true that twisted blades postpone blade stall to higher values of airspeeds. If performance is forced, however, the blade stall is inevitable.

As a helicopter approaches higher and higher velocities, we encounter the basic factors causing stall that were listed earlier. The retreating blade *is losing airspeed. Its angle of attack at the tip is increasing. The loading at the tip is increasing.* Unfortunately, we are not able to arrive at an airspeed at which blade stall will always occur. If this were possible, the problem would be simple. Instead, blade stall can occur at surprisingly low airspeeds under one set of conditions, and still be relatively free from blade stall at high forward speeds under another set of conditions. While its onslaught can be predicted, a number of factors must be considered. Among them are the following:

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Airspeed

Rotor RPM

Gross Weight

Temperature

Altitude

Load Factors (Gust and Maneuvering)

It could be stated in general that blade stall occurs when the rotor is *excessively loaded*. Whichever of the factors just mentioned, whether singly or in combination, result in high rotor loads, blade stall can result. The nutshell rule for the elimination of blade stall once it is suspected is *unload the rotor*! A little analysis and consideration of the listed factors will show many combinations which result in high rotor loads and attendant blade stall.

Now that we have discussed the causes of blade stall, let us examine the effects of blade stall upon the helicopter. Let us start by saying that when the helicopter is in forward flight and blade stall is not taking place, the rotor is in relative harmony. Dissymetry of lift is no problem because of cyclic feathering and flapping hinges. The blades are phased properly except for minor blade movements caused by air loads and Coriolis effect (to be explained later in the text).

Let us depart from this flight condition and increase airspeed. As speed is increased we realize that the airspeed of the retreating blade is decreasing and that in order to maintain its share of the lift, it is utilizing higher and higher angles of attack. In addition the load is shifting toward the tips of the blades as the inflow through the rotor increases. Eventually we reach a speed where the retreating blade tips experience the beginning of blade stall. In light helicopters this is indicated by a vibration felt in the cyclic stick. As the stall condition increases in severity, the vibration is felt in the airframe itself. We also notice that the vibration takes the frequency of the number of blades in the rotor system as applied to one rotation of the rotor. In other words, if the rotor system has four blades, the vibration is a four per revolution or, in the language of common usage, a *four per rev*. This is explained by reference to Figure 65.

In Figure 65 we are not going to identify the angle of attack distribution with any particular rotor configuration other than to state that the rotor has four main blades. We will simply state that under certain conditions, and with preknowledge of the airfoil's stalling point and other characteristics, the airfoil will stall at an angle of approximately 14 degrees. By shading in the 14 degrees contour, we can illustrate the area

65

FORWARD
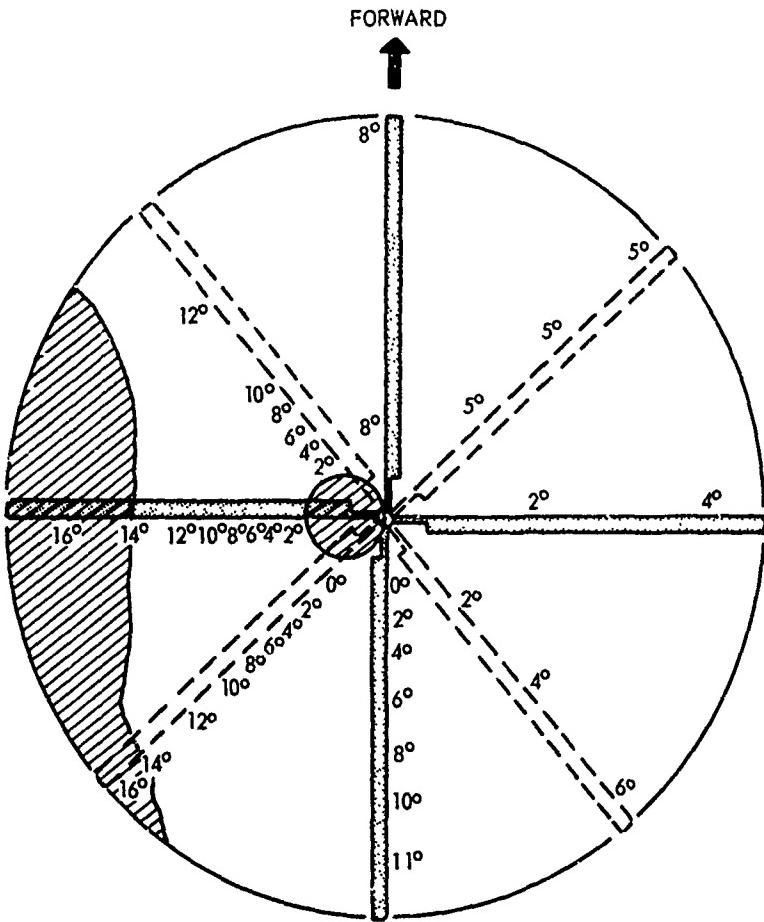
Figure 65 — Angle of attack distribution.

of blade stall with regard to both radial position of the blade and the degree of progression inboard. The solid lined rotor blades show the blades at the longitudinal and lateral axes of the aircraft, and the dotted lined rotor blades show the blades at a 45 degree angle to the major axes.

It should be noted that the tip of the retreating blade has the highest angles of attack and that from the reverse flow area outboard the angle of attack increases very rapidly. The advancing blade, on the other hand, possesses uniform, low angles of attack.

By observation of Figure 65 we can see that under the conditions shown, each blade will enter the stall region on the left side of the helicopter and will remain in that region for about a quarter of a revolution. At the beginning of the region, only the very tip is affected. Half way through the region the stall has progressed inboard on the blade a matter of a few feet. At the end of the region the stall is again at the very tip and from there on the blade is out of the stall area.

66

While each blade is in the stall region, it becomes out of phase with the other blades in the system. This is caused, among other things, by the strong drag variations experienced. Helicopter mechanics are familiar with the one per rev vibration associated with an out of track blade. Blade stall vibrations can be thought of as such a vibration multiplied by the number of blades in the system. Blade stall vibrations can be thought of as a 3, 4, 5, or 6 per rev, depending upon the number of blades utilized in the rotor.

As blade stall begins, the pilot of the small helicopter generally notices an increase in the general vibration level of the helicopter. He will also notice "kicks" in the controls. If he further increases forward speed, moves the cyclic stick forward, reduces rotor RPM, or increases the load factor in any other way, the stall condition will deteriorate to such an extent that the blade pitching moments become so strong that they can overpower the servos with strong, steady vibratory loads manifesting themselves in the control system. It is also apparent that if blade pitching moments are strong enough to overcome the servos, aircraft controllability will become jeopardized. Serious blade stall can result in an uncontrolled pitchup of the helicopter. Naturally, blade stall should never be permitted to degenerate to this extent. If blade stall is suspected, a decrease in forward speed (avoiding rapid flar·   ·educing speed), reduction of pitch, and an increase in rotor speed   reduce the vibration. All of these actions result in unloading the roto,

Blade stall experienced in straight and level flight can generally be recognized in smaller helicopters because the vibratory forces in the controls provide warning of the approaching condition. In the larger, heavier helicopters utilizing servos capable of reacting extremely heavy flight loads, instrumentation is available on some models to warn of the condition.

In maneuvering flight where sharp turns and abrupt pull-ups may be required, severe blade stall can be encountered because of rotor RPM decay or high load factors. Recovery in these cases is much more difficult. The answer, as always, is to unload the rotor. Reduction of collective pitch and/or increasing rotor speed will help.

Previously, we referred to a number of factors that are instrumental in the prediction of blade stall. Among them were airspeed, altitude, rotor RPM, temperature, gross weight, and load factor. It might be intertesting to note the extent of the effect of these factors on the retreating blade tip speed at which stall begins.

In one of Sikorsky's venerable helicopters, no longer in production but

in extensive use in the field, it was determined that in straight and level flight with a gross weight of 7500 pounds and a load factor of one (1), blade tip stall would occur whenever the indicated tip speed of the retreating blade became less than 215 knots. Since the rotational tip speed of that rotor was 348 knots at 2400 engine RPM, stall theoretically would not begin until a forward speed of 133 knots was attained. This situation was rarely met, however, because the aircraft airspeed at which blade tip stall occurred decreased about 15 knots for each 100 RPM decrease in engine speed. It decreased by about 15 knots for each 1000 pound increase in gross weight and/or load factor. It decreased by 4 or 5 knots with each 1000 feet of altitude gain. It decreased by 4 or 5 knots with each increase of 15 degrees Fahrenheit.

From the above factors, it can be seen that while a chart or computor could 'e utilized for the prediction of blade stall, the pilot could not be expected to work changing problems in his head and come out with pinpoint accuracy. He can, however, know and avoid the general conditions conducive to the stall condition. The important thing to remember is that blade tip stall is not solely associated with high aircraft velocities. Under certain conditions, as outlined in the preceeding paragraph, it can occur at surprisingly low forward speeds.

With regard to the aircraft pitch-up that results from severe and ultimate blade stall, it is only necessary to remember that despite the fact that the rotor loses lift on the left or retreating side of the helicopter, the actual settling of the rotor will take place approximately over the tail due to the phase-displacement or, if you prefer, precession of the rotor. Remembering that the rotor is a centrifugally-locked rotating mass, and considering that offset hinges cause the fuselage to tend to line up with the plane of the rotor, rotor-settle over the tail will cause the nose to rise or pitch-up. Following the pitch-up, the aircraft will fall off to one side or the other, generally to the left. As stated before, the pilot who understands blade tip stall will never let the stall condition degenerate to this point. The mechanic who understands blade tip stall will, together with the pilot, fully explore the possibilities of blade stall before initiating a mechanical troubleshooting routine. In the early days many a rotor head, set of blades, and dampers were removed from a helicopter because of a reported vibration that later proved to be blade stall that was not recognized by the pilot.

As mentioned previously, blade stall is not easily recognized in large, heavy helicopters that utilize strong servos to react flight loads. Several years ago a stall warning system was incorporated on one of Sikorsky's large military helicopters. It was required because blade stall was partially

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blamed for several incidents where partial loss of control created uncomfortable situations. Initially a strain gauge instrument located on the stationary star arm over the right lateral servo, it measured vibratory loads emanating from the rotor and, through amplification and associated circuitry, transmitted this information to the pilot by means of an indicator utilizing a needle and a green, yellow, and red operating range. While there is no need to elaborate on improvements made to the system since that time, it nevertheless provided the pilot with adequate intelligence concerning the approach of blade stall. It also proved to be a valuable instrument for determining the loads being reacted by the flight controls. It was invaluable for establishing and monitoring cruise control and fuel management. Maximum cruising speed, especially at high gross weights, is generally very close to the point where drag begins to increase by large increments. The amount of power and fuel required increase very rapidly for very small gains in speed once the rotor enters the stall condition. This drag divergence speed is determined by many factors. Among other things, the stall warning, performance indicator, or cruise guide as it is now called, tells the pilot when he is cruising at speeds conducive to maximum range or whether he is in a partially stalled condition where he may expect excessive fuel consumption. Even at low gross weight conditions, the pilot may utilize the performance indicator to increase his operating range by allowing him to reduce rotor RPM and thus benefit from additional fuel economy without encountering blade tip stall.

With regard to the design considerations of blade stall postponement, we have already discussed the benefits of blade twist. Additional factors to be considered are improvements in the stall characteristics of rotor blade sections, reduction in fuselage drag which will result in a requirement for less rotor tilt at high forward speeds, and the reduction of blade loading by the use of fixed lifting surfaces or additional propulsive devices which unload the rotor as higher forward speeds are achieved. The future will be interesting.

Although not directly stated as such, we have implied up to this point that when cyclic stick is moved out of a neutral position, the virtual axis of the rotor departs from the shaft axis and that in this process the plane of the rotor is locked to the position dictated by the amount of stick movement. In order to avoid confusion, the reference to any other axis has been postponed. In order that the reader may have a full understanding of actual rotor position in response to cyclic stick action, we must mention the *control axis*.

The control axis is the axis of no feathering or cyclic pitch change, or the

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axis of constant pitch. In the hovering helicopter the control axis and the thrust vector or virtual axis of the rotor lie on the same line. A rapid application of cyclic pitch while the helicopter is hovering and before forward speed is built up would still show the control axis and the virtual axis on the same line. In this latter case, of course, the shaft axis is *not* on the same line.
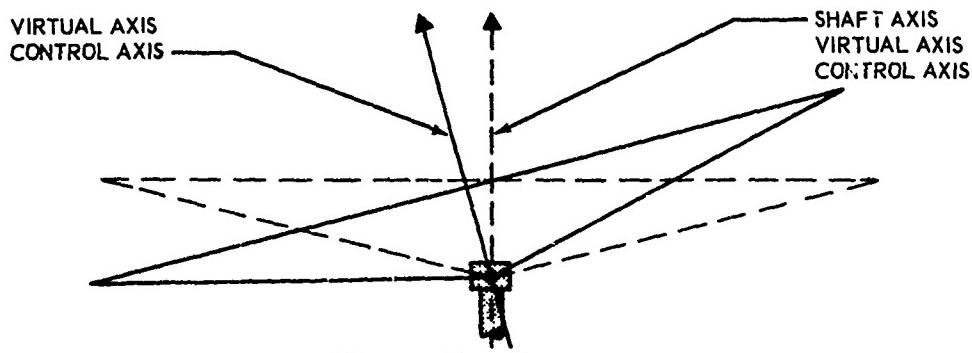

Figure 66 — Rotor axes.

Figure 66 illustrates the fact that when cyclic pitch is applied, the thrust vector (virtual axis) and the control axis depart from the shaft axis. While the use of offset hinges will rapidly move the shaft axis closer to the thrust vector, we have assumed, up to this time, that there could be no separation of the control axis and the virtual or thrust axis. As defined, the control axis is the axis of constant pitch. Note, in Figure 66, that with respect to the control (thrust) axis, the pitch of the blades is constant. Cyclic pitch is only apparent when considered with respect to the shaft axis. The blades *are* feathering about the shaft axis. They are NOT feathering about the control (thrust) axis.

As forward flight continues and forward airspeed is attained, the action of the blades in overcoming dissymetry of lift is going to cause a separation of the control axis and the virtual (thrust) axis of the rotor. This phenomenon is generally called *"blowback"* of the rotor. The separation of the control and virtual axes in forward flight is shown in Figure 67.

In Figure 67 the cyclic pitch stick has been moved forward to tilt the rotor. As airspeed is built up the control axis, established by the amount of cyclic stick utilized, and the virtual (thrust) axis of the rotor begin to separate, with the virtual axis moving aft. (Shaft axis will not be further considered here because its position is determined by other considerations.) As stated previously, this "blowback" of the rotor is caused by the action of the blades in eliminating dissymetry of lift.

Figures 60 and 61 show how dissymetry of lift is eliminated. It was shown that the advancing blade, upon meeting the progressively higher air-
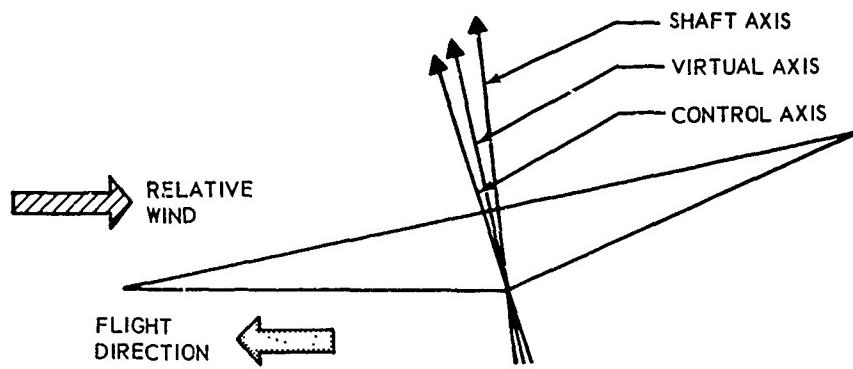
Figure 67 — Various axes in forward flight.

speeds brought about by the addition of forward flight velocity airspeed to rotational airspeed, responded to the increase of speed by climbing or flapping upward. In so doing the change in relative wind and angle of attack reduced the amount of lift that would have been generated. In the case of he retreating blade, the opposite is true. As it lost airspeed, it settled or flapped downward thus changing its relative wind and angle of attack. The resulting larger angle of attack retained the lift that would have been lost because of the reduced airspeed.

Because the flapping velocity, both upward and downward, must be of such a value as to increase or decrease the angle of attack so that the lift will remain constant, it is understandable that the maximum upward flapping velocity will take place directly over the right side of the helicopter and the maximum downward flapping velocity will take place directly over the left side of the helicopter. The flapping velocities are at maximum values directly over the right and left sides of the helicopter because at those locations the airspeed differential is at its maximum.

In our study of cyclic pitch and with particular reference to Figure 34, we were made to realize that in a dynamic system such as a main rotor system with inertia, there was a phase angle between the maximum applied force and the maximum displacement. The force-displacement phase is 90 degrees and it is not affected by blade mass or any kind of air damping. It follows then that if the maximum upward flapping *velocity* is directly over the right side of the helicopter, the maximum *displacement* or actual flapping up of the blade will take place over the nose of the aircraft. Conversely, if the maximum downward flapping *velocity* is directly over the left side of the helicopter, the maximum *displacement* or actual flapping down of the blade will take place over the tail of the aircraft. Figure 68 shows this relationship. The total result of this action is a rotor tilt to the rear which is completely independent of any additional cyclic stick action and

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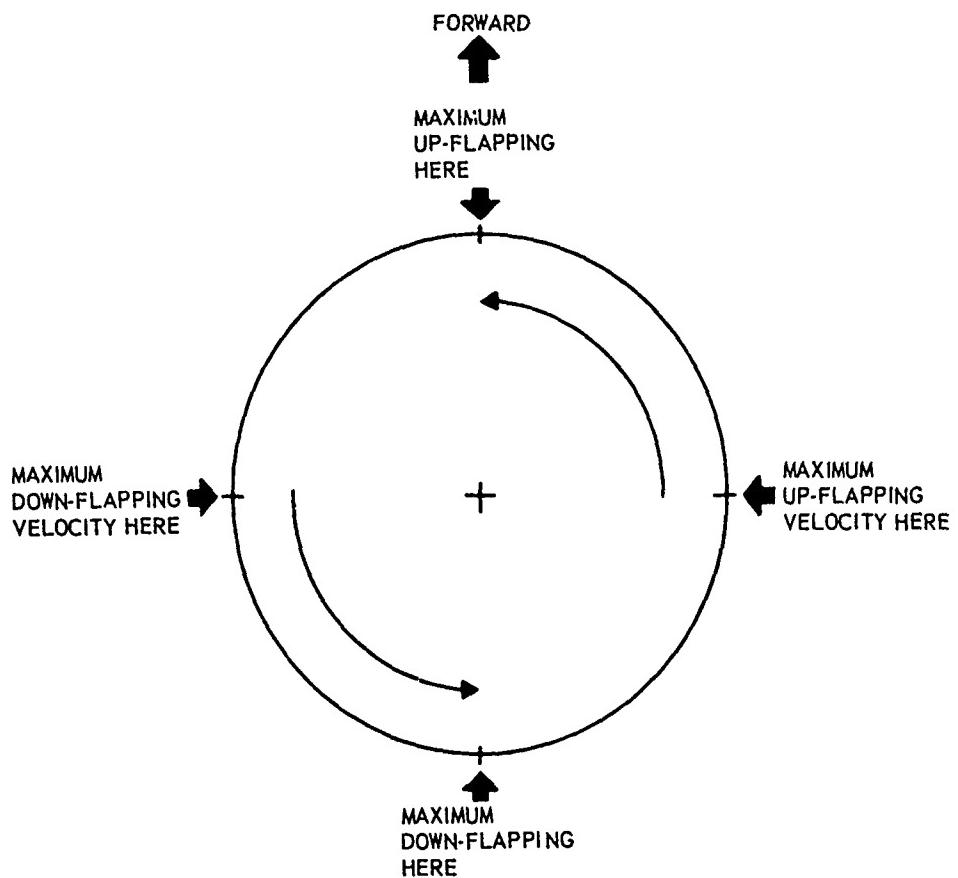
Figure 68 — Blade flapping resulting in blowback of rotor.

which causes an angular separation between the control axis and the virtual (thrust) axis of the rotor.

Just as in the preceding paragraphs we have described how periodic lateral forces cause rotor "blowback" or separation of the control and virtual axes of the rotor, there is yet another periodic force with a phase-displacement angle of 90 degrees. This one, however, arises from periodic longitudinal forces which result from rotor coning while the helicopter is in directional flight. It causes the rotor to tilt to the side.

From Figure 69 it may be seen that the relative wind created by the helicopter's forward flight causes angle of attack differences between the front and rear of the rotor. The blade over the nose of the helicopter experiences an increase in angle of attack because the aircraft relative wind approaches the blade level with or even below its span. The blade over the rear of the helicopter experiences a reduced angle of attack because the aircraft relative wind approaches it from above.

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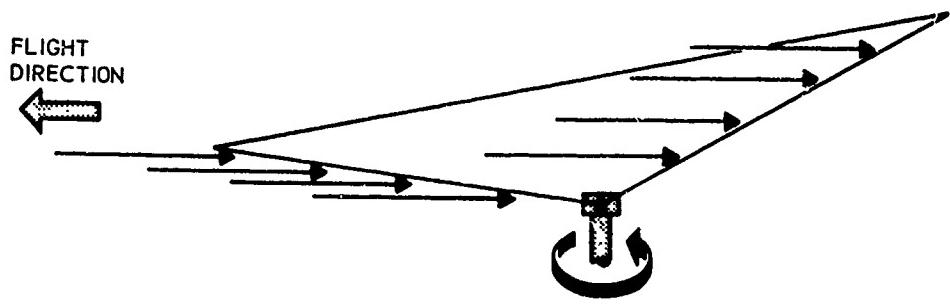
Figure 69 — Airflow in forward flight.

Figure 70 shows that the higher angle of attack at the front of the rotor will cause the blade to flap up over the left side of the helicopter and the lower angle of attack over the rear of the rotor will cause the blade to flap down over the right side of the helicopter. The rotor will thus be tilted a
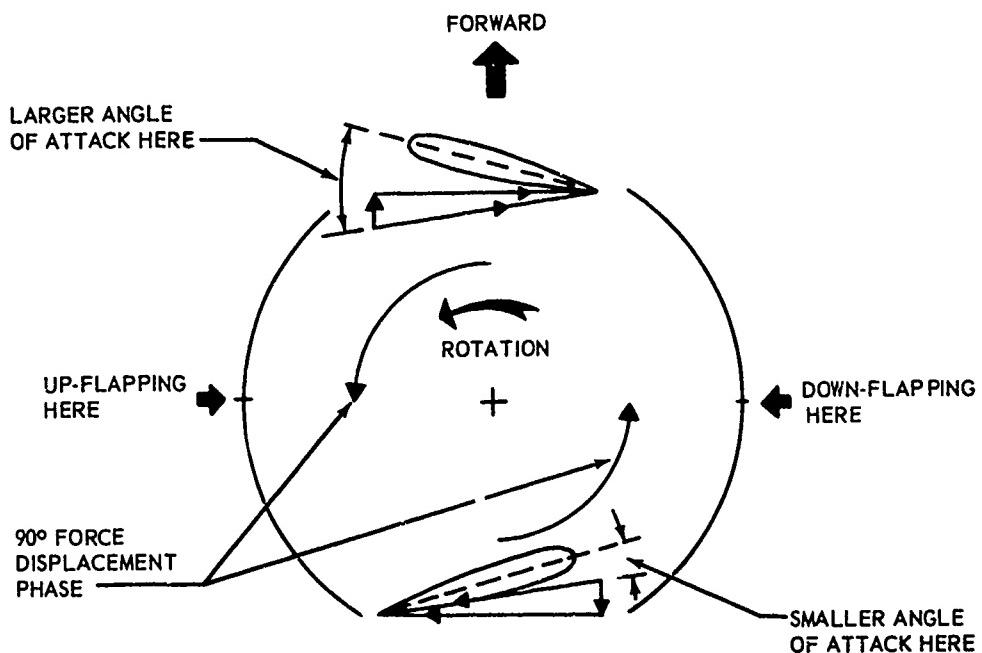

Figure 70 — Angle of attack variaiton causing sideward rotor tilt.

little to the right. The sideward tilt of the rotor is increased at low forward speeds when the induced velocities are large because the inflow not only approaches the rear of the rotor as shown in Figure 69, but is additionally bent downward, thus increasing the angle of attack differences.

The separation of the thrust and control axes arising from these periodic lateral and longitudinal forces is not of serious consequence in the normal operation of the helicopter.

Chapter 5

POWER
AND RELATED TOPICS

Whether discussing a conventional, fixed-wing aircraft or a helicopter, the energy or power required to support or propel the aircraft is divided between:

(a) *The Power Required to Overcome* Profile Drag

(b) *The Power Required to Overcome* Parasite Drag

(c) *The Power Required to Overcome* Induced Drag

(d) *The Power Required to Produce* Climb

(e) *The Power Required to Cause* Acceleration

With reference to purely fixed-wing operation, profile and parasite power are generally considered together. With the helicopter, however, we must consider them separately because of the impact of profile drag on the total power required. The various types of drag were defined in Chapter 1. Profile drag, as you remember, is the frictional drag caused by the rotor blades as they pass through the air. The propeller of the conventional, fixed-wing aircraft also experiences a profile drag, but not of the magnitude of the helicopter rotor.

The power to produce climb is the amount over and above that required for accelerated flight. Without acceleration and in level flight, we have only three basic power/drag factors to consider. They are induced, profile, and parasite. These will be discussed in detail together with a general power required curve.

Before discussing these three factors, let us repeat that in order to keep the helicopter airborne, the rotor must produce thrust. It does this by giving momentum or acceleration to a mass of air which, in turn, produces an upward thrust. It follows that power must be spent to produce this acceleration of the air mass. The amount of power spent is proportional to the velocity of the air beneath the rotor for a given weight of helicopter. This downwash velocity is dependent upon the *amount* of air to which velocity is given in the production of thrust. It stands to reason, then, that a rotor with a large diameter can lift a weight with less induced power required than a small diameter rotor. Additional criteria, however, must be considered when determining rotor diameters. From the statements just made, we can define thrust as equal to the mass of air moving through the rotor per unit of time, multiplied by the total increase in velocity caused by the action of the rotor. You'll recognize this as an application of Newton's Second Law of Motion, $F = MA$ (Force Equals Mass times Acceleration)

With regard to the amount of power available to the rotor and required to overcome the various types of drag, a general estimate for the normal hovering helicopter might be approximately 65% of the total power for the overcoming of rotor induced drag and approximately 35% for rotor profile drag. It should also be remembered that the engine must, in addition to taking care of the rotor losses, supply power to turn the tail rotor and overcome friction in the transmissions and drive system. If the rotor receives more power than is required to overcome profile and induced drag, the helicopter will climb.

Because forward flight is a helicopter requirement, it is interesting to note the effect of forward speed as it pertains to the various types of drag and the power required to overcome them. Please note that the power required diagrams that follow are intended to illustrate only general power trends and no attempt has been made to furnish accurate figures or performance criteria.
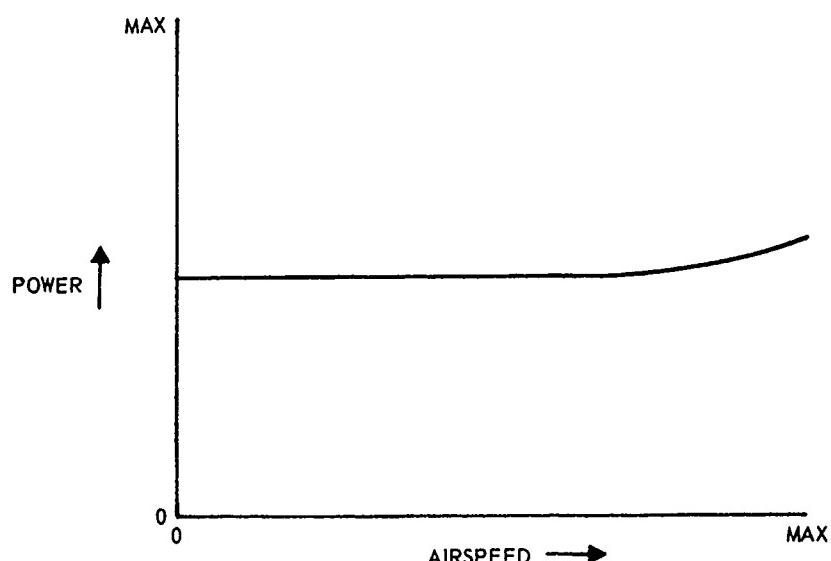

Figure 71 — Profile power.

In Figure 71, the Profile Power Required Curve, it should be noted that a substantial amount of the power available is required to turn the rotor through the air against aerodynamic frictional forces. Since rotor speed is relatively constant, profile drag power increases only slightly as normal forward speed is increased. At *very high* forward speeds and *as blade stall is entered*, profile drag losses mount rapidly. Once blade stall is entered, the addition of only 3 or 4 degrees of angle of attack on the blade in the stall region can cause an almost doubling of profile drag losses.

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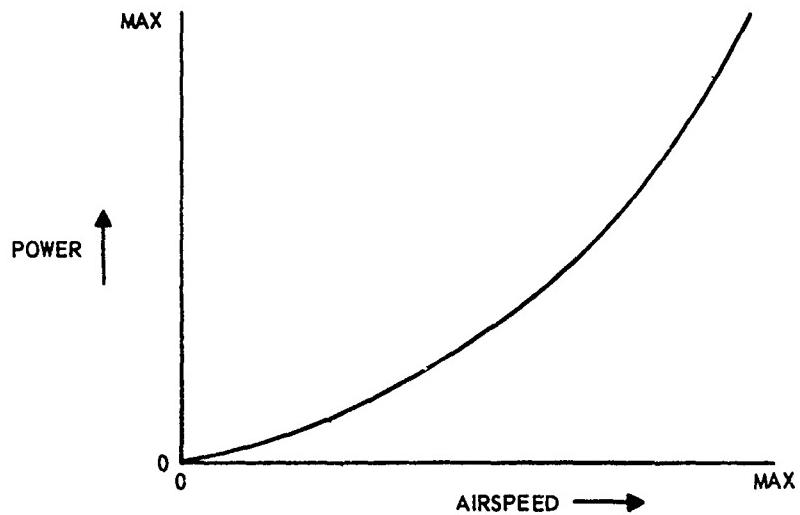
Figure 72 — Parasite power.

Figure 72 illustrates a general curve denoting the relationship between parasite power and airspeed. It stands to reason that at zero airspeed, there would be no expenditure of power to overcome parasite drag. As the helicopter picks up airspeed, however, parasite power required, varying as the cube of the airspeed, increases very rapidly at higher speeds. The more aerodynamically clean the helicopter is, the better the picture with regard to parasite drag losses. (The same may be said for rotor *blade* cleanliness with regard to profile drag losses.)
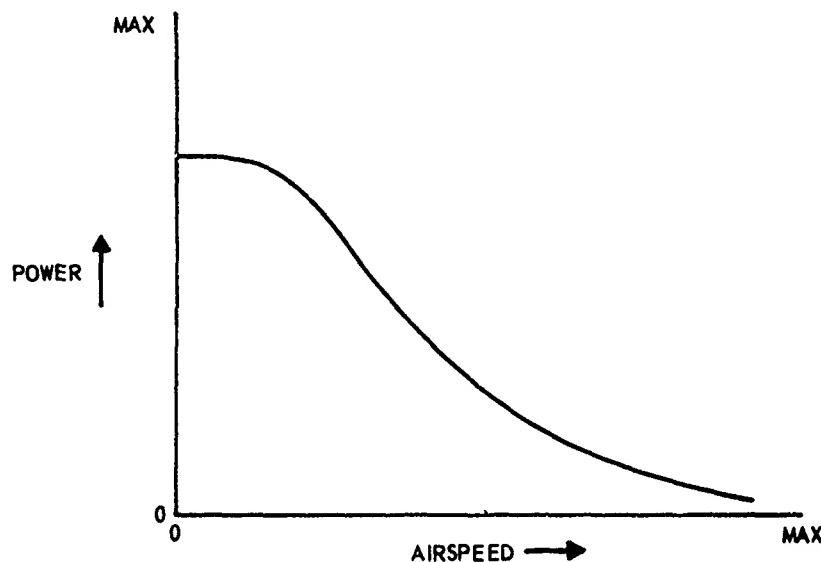

Figure 73 — Induced power.

In Figure 73 it should be noticed that at zero airspeed, the induced power requirement is fairly high. This is so because the rotor must impart consid-

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erable energy to produce the jet of air moving through the rotor. As stated previously, the power required is proportional to the downwash velocity for a given weight of helicopter. In the hovering helicopter, the downwash velocity is near maximum value. The downwash velocity, and consequently the induced power required, decreases with forward speed. It reaches its lowest value in the middle ranges of speed. The reduction of induced power required with forward speed is caused by the fact that as the rotor moves forward, *it meets a larger mass of air per unit of time.* To generate the desired amount of thrust it does not have to impart as much velocity to each mass of air, and the energy imparted to the air is reduced. Downwash velocity is reduced. Unfortunately this happy situation cannot progress to much more than the middle ranges of airspeed due to rapidly rising parasite drag losses.
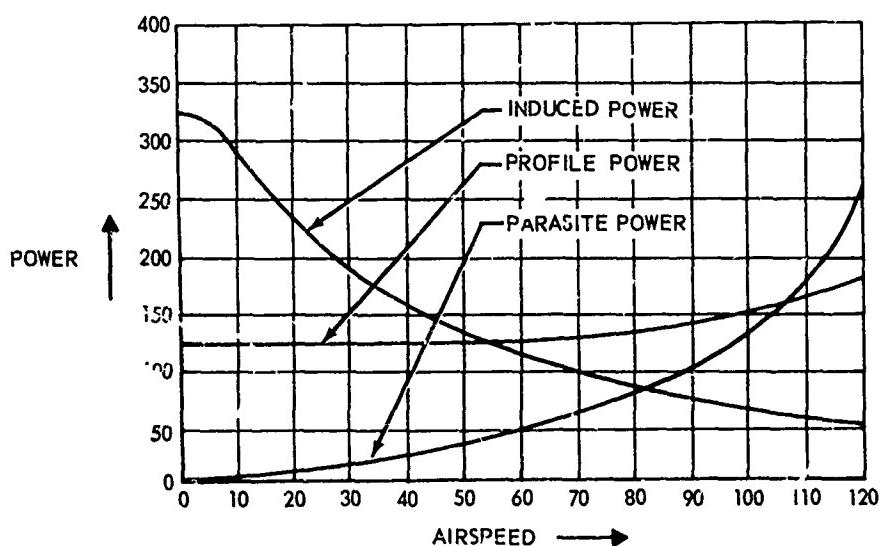

Figure 74 — Power distribution.

The curves and values shown in Figure 74 should not be taken as performance criteria for any helicopter and should be viewed only as a method of showing the trend of induced, parasite, and profile power with airspeed. In an accurate illustration drawn for a particular helicopter the sum of the values of each of the curves at any given airspeed would give the total power required for level flight at that speed. An approximation of a resultant power required curve is offered in Figure 75.

In Figure 75 it can be seen that the power required to hover is quite high due to the high induced velocity required to produce the necessary thrust. The power required then decreases quite rapidly in the middle ranges of speed as a result of decreasing induced power losses. It builds
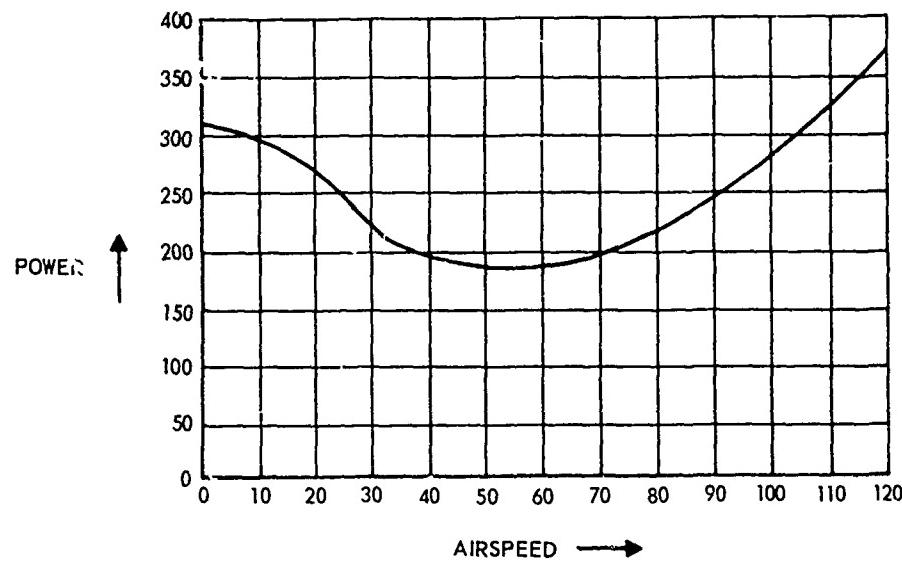
Figure 75 — Power required.

up again at the higher speeds due to the high values of fuselage or parasite drag.

If your interest is in minimum power for level flight, it can be seen that the middle ranges of airspeed will produce the lowest requirement for power and fuel. It can also be stated that the best airspeed for climb will be the one where the most power is available. This is the airspeed at which minimum power is required for level light.

The most important factor in the consideration of performance in a helicopter is the relationship between the power available and the power required. We can define the power available as the rated power of the engine less the power required to operate the tail rotor, engine and transmission cooling fans, and frictional losses in the transmission and other elements of the dynamic system.

As illustrated in Figure 76, for a helicopter with adequate power, there is ample power available to permit hovering and climbing. The diagram illustrates the relationship between power available and power required. Good performance characteristics would be evident in this case.

Because of the characteristic downward slope of the induced power required curve as airspeed is built up, it is possible to fly an overloaded or underpowered helicopter even though vertical flight or hovering is impossible.

This situation is illustrated in Figure 77 where the weight of the helicopter is such that more power is required to make it hover than is available. Reference to the diagram shows that the power required and power

POWER

POWER AVAILABLE

EXCESS POWER

POWER REQUIRED
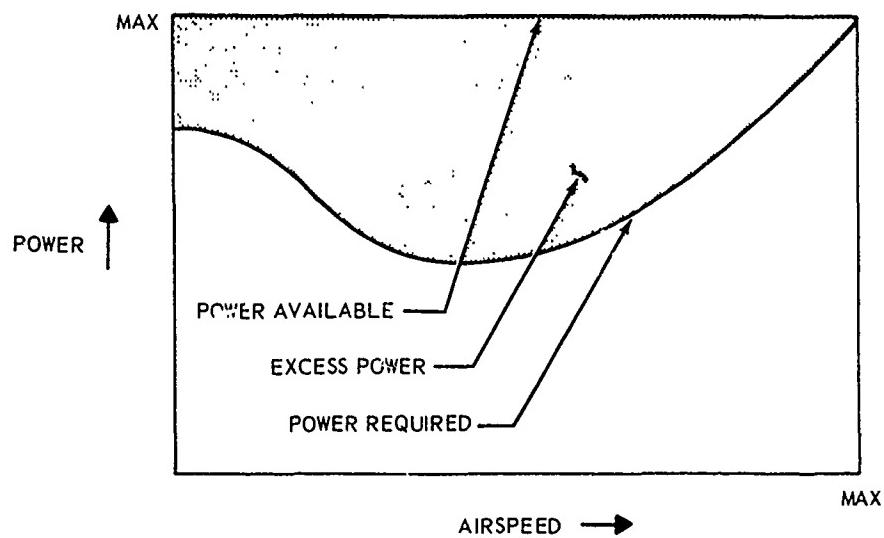
AIRSPEED

Figure 76 — Excess power.

available lines cross at approximately 20 miles per hour airspeed. If the pilot makes a ground run the helicopter will pick up airspeed. At any airspeed over 20 miles per hour power available increasingly exceeds power required to become airborne, and excess power is developed for climb or maneuver. The same phenomenon would be noticed if the pilot made a vertical takeoff into a surface wind blowing in excess of 20 miles


POWER

POWER AVAILABLE

EXCESS POWER

POWER REQUIRED

0   10   20   30   40   50   60   70   80   90   100   110
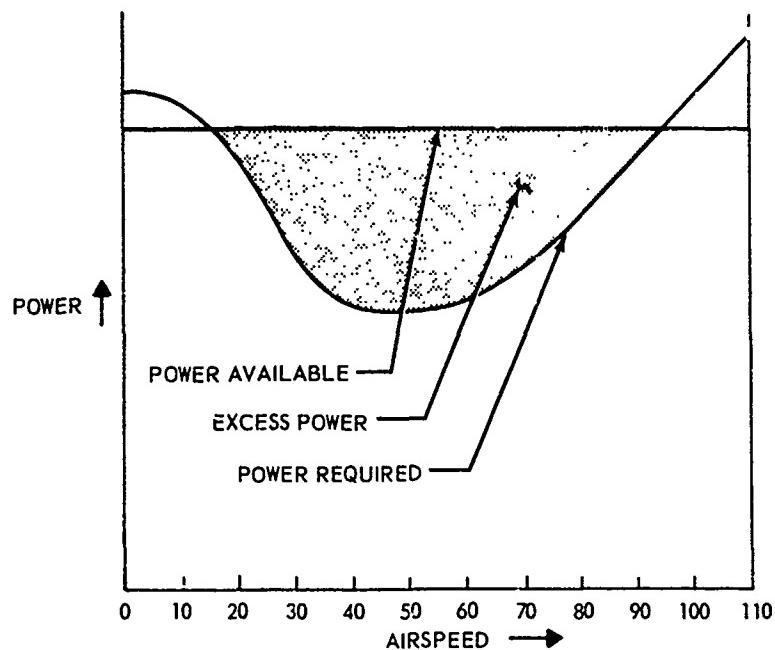
AIRSPEED

Figure 77 — Insufficient power.

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per hour. To the rotor, airspeed is airspeed whether it is derived from forward flight in the air, from rapid taxiing on the runway, or from a strong surface wind.

This phenomenon is known as *transitional* or *translational lift*. Substantially it is simply the changing relationship between power required and power available brought about by introducing the rotor to larger masses of air per unit of time or, in other words, giving the rotor airspeed regardless of the source of such speed.

On the first page of this chapter it was stated that power required is proportional to the downwash velocity (induced velocity) for a given weight of helicopter. In essence this is illustrated in the description of transitional lift. Induced power is reduced because the induced velocity decreases with forward speed. There is yet another way for a helicopter in flight to experience a reduction in induced velocity with an attendant saving in power. It is by means of the phenomenon known as *ground cushion* or *ground effect*.

The effect of ground cushion is not confined solely to helicopter operation. Its effect is well known to pilots of fixed wing aircraft, especially those in the light weight category. There are times when trying to get a very light airplane back on the ground becomes rather amusing and, at other times, not so amusing — especially when the fence at the other end of the field is getting closer and closer.

Ground effect as applied to helicopter is a most useful flight tool. It enables underpowered or overloaded helicopters to hover by taking advantage of the lower power required for a given thrust when operating in close proximity (one half rotor diameter) to the ground. While ground cushion has sometimes been described as the compressing of air between the rotor and the ground, it is probably best to consider the relationship between induced velocity and power required. When a helicopter is hovering close to the ground or any structure with a fairly large, flat landing surface, the ground or surface acts as a huge brake to the downwash. This restraint of the rotor downwash occurs as the helicopter reaches an altitude just a few feet off the ground. Because the induced velocity required to produce a given amount of thrust is reduced, there is a corresponding decrease in required induced power. It follows that any decrease in induced power results in more power being available for other use. It is also true that if a fixed amount of power is being transmitted to the main rotor shaft, movement onto the so-called ground cushion will produce additional thrust.

While ground effect is greatly beneficial and helicopter performance charts indicate hovering ceilings in and out of ground effect, some caution is called for in certain types of operation, especially with marginally powered helicopters. Operating from buildings, ships, platforms, or even certain types of terrain under marginal conditions, can cause ground effect on half the rotor with the other half being out of ground effect or simply intermittant ground effect. The attendant possible settling could be troublesome.

No discussion of power as it applies to helicopter operation would be complete without mention of a phenomenon known as *power settling*. At high altitudes, high gross weights, or when operating with reduced power, it may not be possible to maintain level flight due to a lack of power. The resulting settling of the helicopter is not too important except at certain combinations of rate of descent and low airspeed. When operating at these combinations, the attendant power settling becomes critical.

Aerodynamic analysis of power settling shows that when a critical power settling condition occurs, roughness and a degeneration of control effectiveness results. As we have seen from previous discussions, rotor downwash approaches maximum values when the helicopter is at or near the hover. Under certain power and rate of descent combinations a vortex ring flow state occurs through the rotor. Vortices are built up at the tips of the blades and in the center of the rotor. A gigantic recirculation of air takes place in and around the rotor. The helicopter settles into the air mass its rotor has just displaced in its attempts to produce adequate lift. The blades attempt to maintain efficiency but fall short of the desired .goal because they are working in their own turbulence.

In extreme power settling, the velocity of the recirculating mass becomes so high that full collective pitch and power will not produce sufficient thrust to slow down or control the rate of descent which can easily exceed 3000 feet per minute. Recovery from this condition is made by increasing forward speed (airspeed), decreasin collective pitch, or entering autorotation if altitude and other condi permit. As can easily be seen from the above description, considerable loss of altitude may be experienced before power settling is recognized and recovery effected. Because of this fact, conditions tending to cause power settling should be avoided at low altitudes.

As a last thought on this subject, under certain conditions of high altitude, high gross operation, the airspeed envelope between power settling and blade tip stall may be quite small.

Chapter 6

ROTOR DYNAMICS

In Chapter 3, while discussing average blade lag angles, it was pointed out that there would be a minor leading and lagging of the blade about the average lag angle when cyclic pitch is applied to the rotor. It was also stated that varying air loads would cause some periodic in-plane movement of the blade about the drag hinge.

It is quite easy to see that because the blade is subject to varying air-speeds and varying angles of attack during rotation, a certain amount of in-plane movement is inevitable. The movement of the blade in the plane of rotation caused by periodic mass forces is a little more complex. In mathematics these forces are called Coriolis after the mathematician who made a study of them. Before applying these forces to a rotor system however, some discussion of the basic forces might be in order.

The law of *Conservation of Angular Momentum* states that the value of angular momentum of a rotating body will not change unless external torques are applied. In other words, a rotating body will continue to rotate with the same rotational velocity until some external force is applied to change the speed of rotation. Angular momentum can be expressed as:

Mass X Angular Velocity X Radius squared

Changes in angular velocity, known as angular acceleration or deccelera-tion, will take place if the mass of a rotating body is moved closer to or further from the axis of rotation. Acceleration will take place if the mass is moved closer to the axis of rotation and deceleration will take place if the mass is moved further away from the axis of rotation. The speed of the rotating mass will increase or decrease in proportion to the square of the radius.

Most of us have seen an excellent example of this principle when watching a figure skater on ice skates. The skater begins a rotation on one foot, with the other leg and both arms extended. The rotation of the skater's body is relatively slow. When the skater draws both arms and the other leg inward, his body is suddenly rotating almost faster than the eye can follow. When he pulled his arms and leg in, his moment of inertia (Mass times Radius Squared) became much smaller. Because his angular momentum must, by law of nature, remain the same (no external force was applied), his angular velocity had to increase.

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The mathematician, Coriolis, was concerned with the forces generated by such radial movements of mass on a rotating disk or plane. These forces, which cause acceleration and deceleration, bear his name.

TANGENTIAL VELOCITY

RADIAL VELOCITY
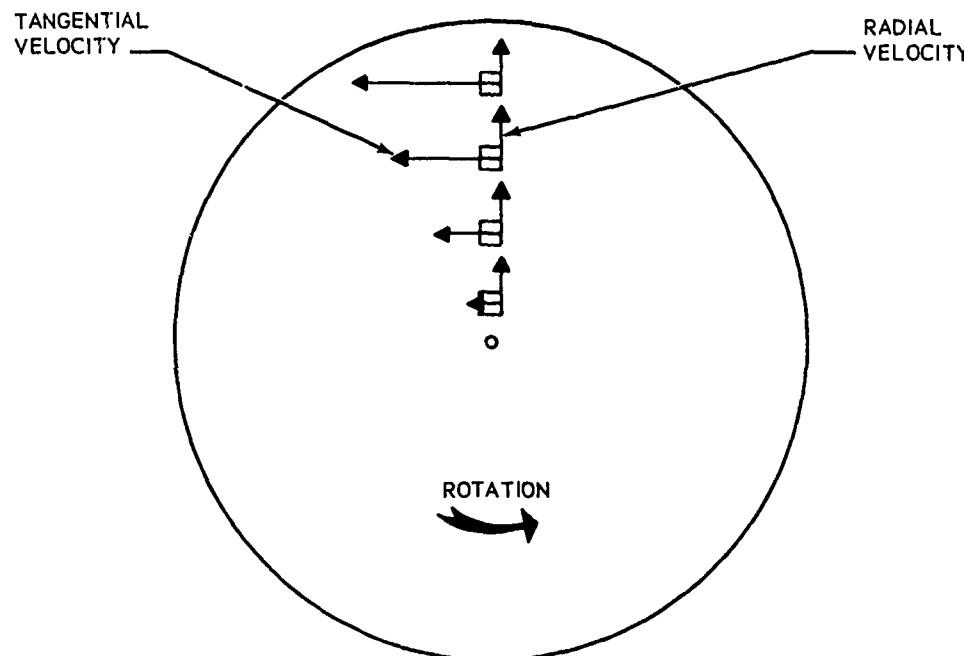
ROTATION

Figure 78 — Rotating masses.

In Figure 78 a mass is being moved radially outward at constant velocity on a rotating disk. As its radius is increased, the mass is experiencing a progressive increase in its tangential velocity. According to Newton's Law, any mass will resist a change in velocity. The outward moving mass in Figure 78 resists the tangential acceleration to the left by exerting a force to the right on its surroundings. If it were moving radially inward on the rotating plane, the opposite would be true. Considering this resisting force in terms of rotation, it may be stated that:

A mass moving radially outward on a rotating disk will exert a force on its surroundings *opposite to rotation*!

A mass moving radially inward on a rotating disk will exert a force on its surroundings in the *direction of rotation*.

Now let us apply this concept to a rotor system. First of all, what is there in the rotor system that has mass? Obviously the major rotating

elements in the system are the rotor blades. A center of mass can certainly be established for the rotor blade.
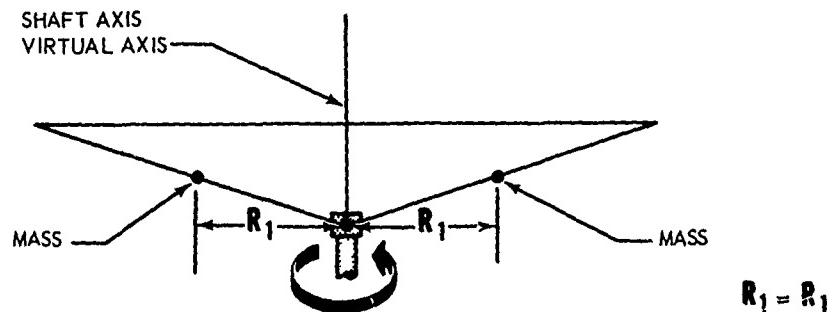

Figure 79 — Blade mass on coned rotor with no tilt.

In Figure 79 we see a diagram of a rotor viewed from the side. It is rotating. The shaft axis and the virtual axis of the rotor are the same. The blade center of mass has been located. No Coriolis force is present because the radius of the mass is constant. It is neither moving toward nor away from the center of rotation. As the rotor is turning at constant rotational speed, the speed of the blade mass is proportional to its radius.
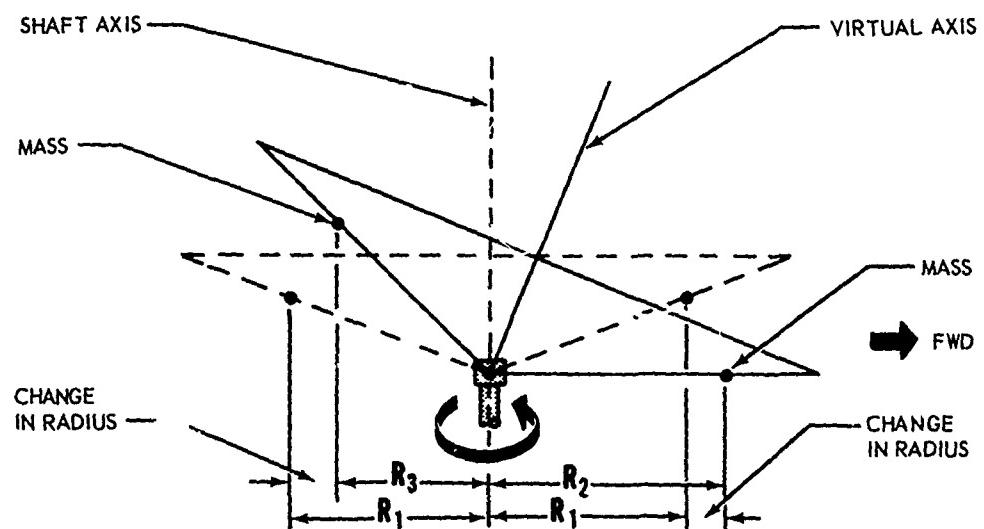

Figure 80 — Blade mass movement on cyclically tilted rotor.

The *dotted* rotor outline in Figure 80 duplicates the situation shown in Figure 79, with no blade flap and the blade mass rotating at constant radius, R_1. The *solid* lined rotor has cyclic pitch applied. It is tilted with respect to the main rotor shaft. The shaft axis and the virtual axis of the rotor no longer fall upon the same line. The forward blade is flapping down and the rearward blade is flapping up. Notice that the mass of the

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low flapping blade has moved further away from the axis of rotation (Radius R_2) while the mass of the high flapping blade has moved in toward the axis of rotation (Radius R_3). Whenever the shaft axis and the virtual axis of the rotor are not the same (when cyclic pitch is being applied), the radius of the blade mass will not be constant and it will have a periodic velocity toward or away from the center of rotation.

We have stated before that any rotating mass which also has a velocity toward the center of rotation generates a Coriolis force in the direction of rotation. When the velocity is away from the center of rotation, the Coriolis force is opposite rotation. The first is an accelerating force, the second a decelerating force.

The total force on the blade is the sum of the forces on the individual elements. In the cyclically tilted rotor Coriolis forces cause the blades to hunt forward or backward (lead and lag) (accelerate or decelerate) just enough so that the forces stay in balance and angular momentum is conserved. This produces a hunting motion of the blades of about 1 to 2 degrees forward and aft of their mean lag angle.
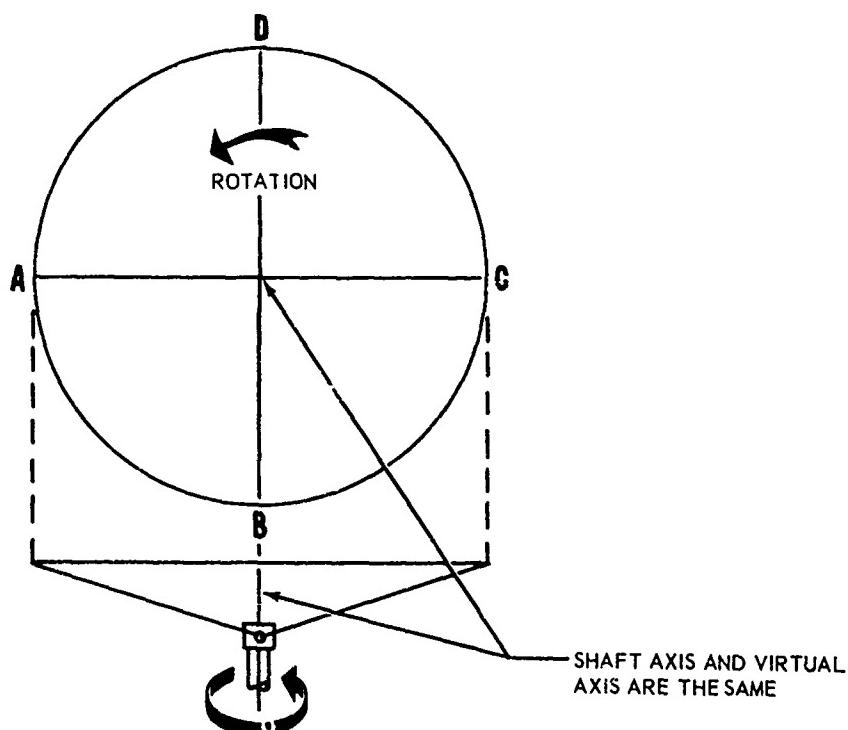

Figure 81 — Coned rotor references.

In Figure 81 we see a side view of a rotor with coning. We also see the rotor viewed directly from above. No cyclic pitch is applied. The

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virtual axis of the rotor and the mechanical shaft axis are the same. In obeyance to the law of conservation of angular momentum, the tips of the blades have constant angular velocity and are passing from A to B to C to D in the same units of time.
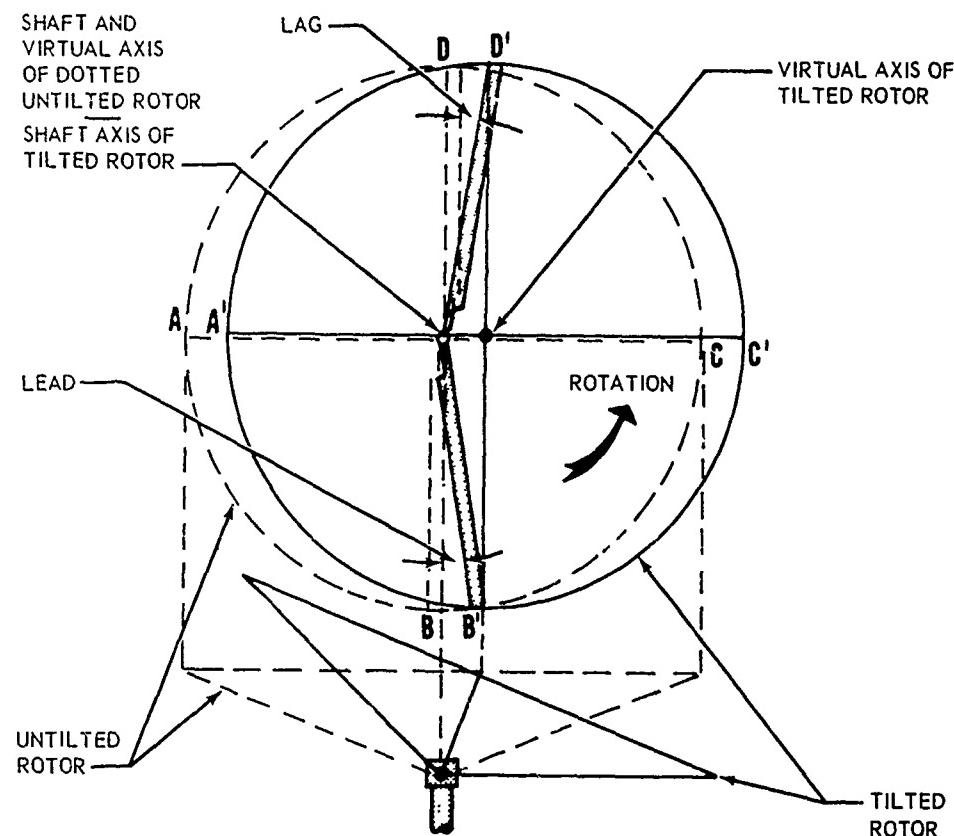

Figure 82 — Reference changes on cyclically tilted rotor.

In Figure 82 the dotted rotor illustrates the same rotor shown in Figure 81. Shaft and virtual axes are the same. There is no cyclic pitch, no rotor tilt. The tips of the blades are passing from points A to B to C to D in the same units of time.

In Figure 82 the solid lined rotor has cyclic pitch applied. The rotor is tilted with respect to the shaft. The shaft axis and the virtual axis are not the same. The center of the rotor or virtual axis has moved forward and the blades are passing from points A' to B' to C' to D' in the same units of time in order that angular momentum may be preserved. Note however, that when the rotor was tilted forward, *the shaft axis did not tilt with it!* The blades, which are attached to the hub, are rotating about the shaft axis but the tips of the blades must pass from A' to

B' to C' to D' in the same units of time. In order for the blade, which is attached to the mechanical shaft axis, to get past point B to point B', it must lead. Swinging around the left side of the helicopter the blade does not have to go all the way to D, it need only get to point D'. As a result, it lags. The terms leading and lagging are synonymous with acceleration and deceleration. By coupling the mathematical analysis of the periodic changes of mass radius and its resultant acceleration and deceleration forces with the visual presentation shown in Figure 82, we can see that while the *tips* of the blades maintain angular momentum, the remaining portions of the blades do the actual leading and lagging, the acceleration and deceleration. If the last sentence is not clear, just remember that the tips of the blades, due to unchanging angular momentum, are passing through points A', B', C', D', in exactly the same unit of time *and those points are 90 degrees apart*! If it were possible for you to stand on an extension of the shaft axis and look down on the tilted rotor, you would see the blades periodically moving back and forth in the plane of rotation — in other words, leading and lagging. If you could stand on an extension of the virtual axis of the tilted rotor, you would see the blades rotating, evenly spaced and phased, with no leading and lagging.
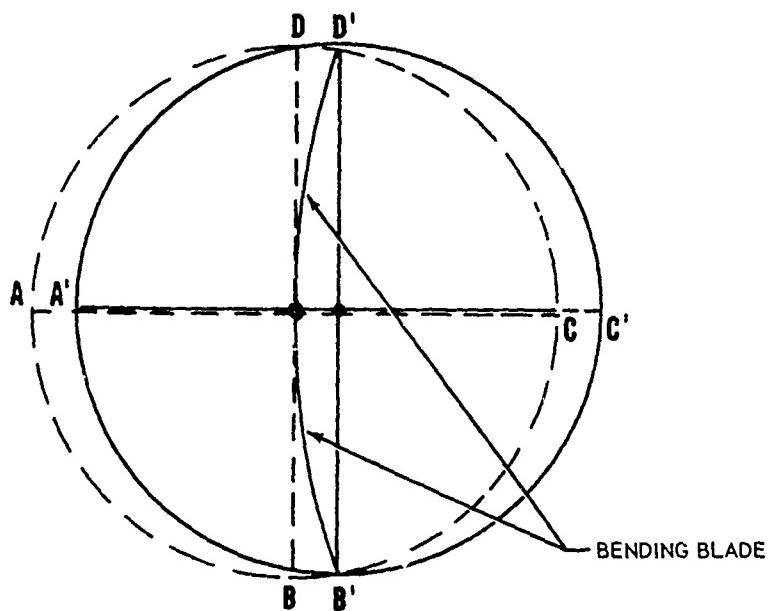

Figure 83 — Lead-lag bending of rigid rotor.

In Figure 83 we will assume that the blades in the rotor have no drag hinges about which they can hunt. They are rigid in the plane of rotation. Notice that as the rotor is tilted with respect to the shaft, the tips of the

blades pass through points A', B', C', and D' in the same unit of time even though the roots of the blades are attached to the hub which did not move forward with the virtual axis of the rotor. In order for the blades to pass through the prime (') points, *the blades must bend* as indicated by the curved blades in the diagram. These in-plane bending moments in the blade would be transmitted to the main rotor shaft and would cause vibrations in the entire helicopter if they were not relieved. Blade life would be greatly reduced by these oscillating shear loads. These forces are relieved by the addition of drag hinges which permit the blade to hunt in the plane of rotation according to the periodic air load and mass forces involved.

From our discussion of Coriolis forces, we can see additional reasons for the use of the fully articulated rotor head with offset hinges. It is unfortunate, however, that in the solving of one problem, we sometimes create another. The addition of drag hinges substantially relieved the in-plane bending moments caused by periodic air loads and mass forces, but in giving the blade freedom of movement in the plane of rotation, the door was left open to another problem, namely, *ground resonance*.

Of the two types of vibrations found in helicopters, ordinary and self-excited, ground resonance is of the self-excited type. Self-excited vibrations need no periodic external forces to start or maintain them. When a coupling or interaction occurs between the movement of the rotor blades about their drag hinges and a fore-and-aft or sideward movement of the main rotor shaft (i.e., the whole aircraft), the result is a self-excited vibration. During resonance, the helicopter rocks fore-and-aft or sideways with increasing magnitude, with the rotor blades weaving back and forth in the plane of rotation and out of pattern. The phenomenon is known as ground resonance because the vibration occurs when the aircraft is on the ground supported by its relatively soft tires and oleo struts, a support conducive to a low frequency movement of the aircraft either fore-and-aft or sideways. This instability, created by the interaction of a helicopter's rocking on its tires and the oscillation of the blades about the drag hinges, can cause destruction of the aircraft. During ground resonance, the blades are definitely out of pattern. If one blade leads while an adjacent blade lags, the resultant out-of-balance condition of the rotor causes the shaft axis to follow the heavy or more centrifugally loaded section of the rotor. Because both the rocking and the movement of the blades in and out of pattern excite each other to greater magnitudes, ground resonance forms an excellent example of negative stability or negative damping. Figure 84 illustrates how blades out of pattern can bias the centrifugal balance of the rotor system. The shaded portion of the rotor is the heavy side. Following
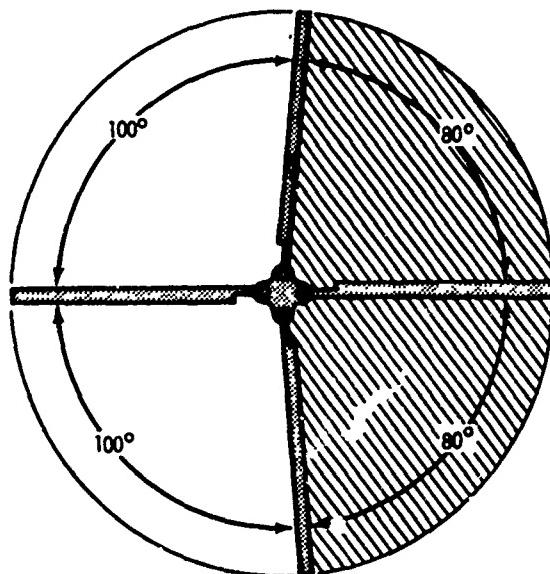
Figure 84 — Blade motion in ground resonance.

the heavy side of the rotor, the shaft will describe a circle or eccentric which will cause the aircraft to rock.

To reiterate, two conditions must exist to cause ground resonance. First, there must be some abnormal lead/lag condition which dynamically unbalances the rotor. This could be caused by a blade badly out of track, a faulty damper, or a peculiar set of landing sequence conditions. Secondly, a reaction between the aircraft and the ground via tires or struts which would aggrevate and further unbalance the rotor. When, during the course of a landing, a wheel reaction occurs that would cause a set of blades already out of pattern to become even further out of phase, and this out-of-phase condition progresses to the point of maximum lead and lag blade displacement, ground resonance will undoubtedly occur. A hard, one-wheel landing with a tricycle landing gear would be an example of such a situation.

Many pilots will remember instances when a helicopter went into ground resonance when it was in the process of slowly lifting off the ground or was partially airborne. This was particularly true when the helicopter landing gear utilized air-oil struts (oleo). The rate of the air spring in the strut varies with its deflection thus causing the helicopter's natural frequency to vary according to the amount of weight on the gear. A helicopter might be quite stable when all its weight is on the ground, but might experience instability when partially airborne.

When resonance is suspected and rotor RPM is within operating range, the immediate application of power and a rapid takeoff will stop the condition. By becoming fully airborne the helicopter's natural frequency changes.

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As rolling and lateral natural frequencies attenuate, the interaction or coupling between the blades and the airframe is destroyed and the condition ceases.

Adequate system damping and control of the helicopter's natural frequencies have, to all extents and purposes, practically eliminated ground resonance as an operating problem. Engineers accomplished this by refinements resulting from intimate studies of blade dampers, oleo struts, spring rates, tire / spring rates, and landing gear types and treads.

It is apparent that drag hinges are mandatory. It is also apparent that the drag hinges permit the movement of the blade in the plane of rotation which, when the aircraft is on the ground, can result in resonance when coupled with other factors. In flight, we desire that the blades have substantial freedom of movement in the plane of rotation. On the ground we would like to have the blades fixed in the plane of rotation. Obviously some sort of a compromise is called for. Let us now introduce the *damper*.
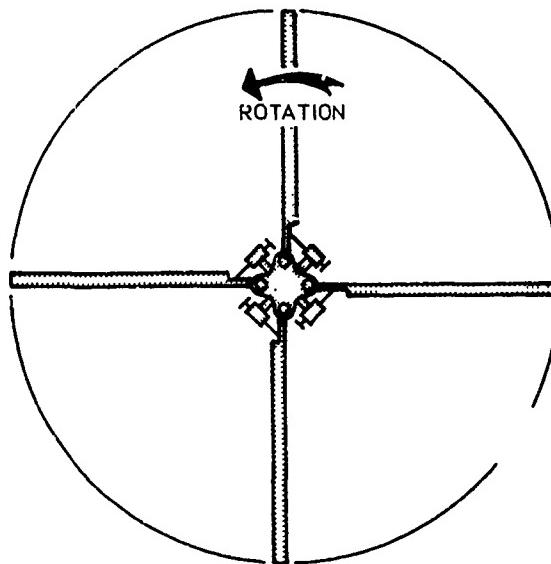

Figure 85 — Rotor with blade dampers.

The damper is a unit consisting of a cylinder, piston, and piston shaft. The cylinder or housing, as shown in Figure 85, is attached to the rotor head aft of the blade it is serving. The forward end of the piston shaft is attached to the drag hinge (i.e. the blade). The movement of the blade is restrained because hydraulic fluid must flow from one side of the piston to the other through a restricted orifice.

The action of the restricted orifice inhibits the in-plane movement of the blade sufficiently to keep the blades in phase during ground operation.

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Adequate freedom of in-plane movement of the blades in flight is assured by the use of a pressure relief valve located in the piston. These valves open at settings varying from 125 PSI in the smaller helicopters to near 400 PSI in the larger models. In-plane movements of the blade in flight, dictated by varying air loads and/or Coriolis forces, are not adversely limited by damper action. A primary utility of the damper lies in its resonance inhibiting abilities.

As a matter of interest, ground resonance is the only major self-excited vibration applicable to helicopters utilizing fully articulated rotor systems. It was given coverage in this text only because the term is well known, because of its safety implications, and to explain the requirement for in-plane blade freedom in flight and restraint on the ground. Rotor stimulated vibrations which occur at frequencies that are even multiples of rotor speed, structure frequency excitation by intermittant air forces, and all other types of ordinary vibrations will not be discussed as they are beyond the intended scope of this publication.

Of interest to maintenance personnel, however, is the fact that vibrations can be classified into three basic categories. They are of low, medium, and high frequencies. Low frequency vibrations stem from the unit with the lowest RPM which is, of course, the main rotor. If these vibrations are abnormal, all elements of the blades and rotor head assemblies are suspect. Rotor blades, for example, could be out of track or physically damaged. They could be out of spanwise or pitching moment balance. Many things can cause variations in profile drag (dirt, etc.). In the rotor head it would be well to look for inadequate lubrication, binding of components, excessive play in and between components, improper torques, bad dampers and bad bearings, to mention just a few.

Medium frequency vibrations generally stem from the tail rotor assembly. Troubleshooting this vibration calls for roughly the same procedure as used with the main rotor. High frequency vibrations generally originate from the engine and shafting being driven at high RPM. Maintenance handbooks generally give directions for the isolation of vibration troubles.

From the pilot's viewpoint, there is one more vibration that is fairly noticeable and that requires some discussion. It is the vibration or shake encountered during the transition from hovering to forward flight and from forward flight back to hovering.

As previously discussed and as illustrated in Figure 86, the inflow through a rotor added to the relative wind due to rotation creates a resultant relative wind which reduces the angle of attack to a value smaller than the pitch angle. As forward cyclic pitch causes the helicopter to move for-

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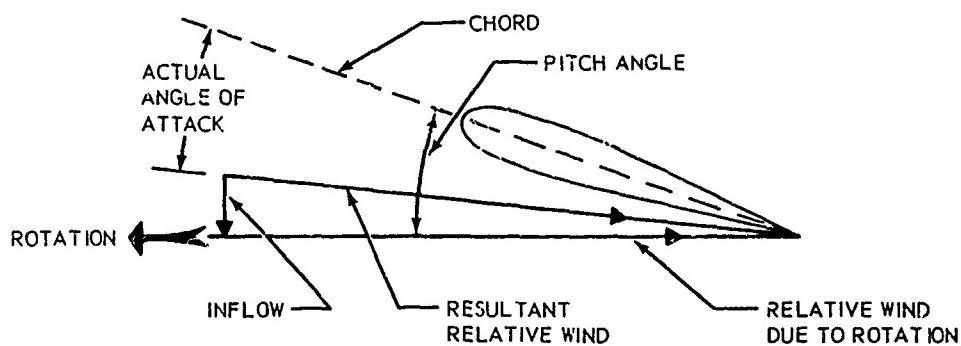
Figure 86 — Blade angle of attack considering inflow.

ward, the advancing blade progressively reaches out beyond the hovering inflow into undisturbed air. Since the pitch has already been set and since the inflow velocity decreases, it can be seen that a local increase in angle of attack will take place on the blade with a corresponding increase of lift near the tip. Instrumentation has proved that a substantial upward bending of the blade takes place from the time it leaves the right side of the helicopter until it reaches a point about half way between the nose and the left side. Pilots note this effect by the large forward cyclic stick displacement necessary to attain nominal increments of speed up to approximately 40 knots. From our understanding of rotor control, it can be seen that the forward cyclic control reduces the pitch on the advancing side to compensate for the local high angle of attack, but it also increases the pitch on the retreating blade to a higher value than is actually required. These two local increases in angle of attack cause a discontinuity in the smooth, normal lift variation of the rotor disk and result in roughness. The magnitude of this vibration is dependent upon pilot technique to a large extent. If the cyclic control is moved far enough forward to accelerate reasonably quickly to best climb speed, and collective control is increased sufficiently to permit this action, the vibration level during this transition will be relatively minor.

An additional cause of roughness during speed reduction as an approach to a landing is made is occasioned by the blades passing through the wake of preceding blades as the helicopter loses altitude. At certain advance ratios of forward speed to tip and sink speeds, this power settling seems to be .t a maximum. Vertical descent with partial power appears to be the worst out of ground effect. Ground effect seems to spread the wake and possibly intensify it, so that power settling in ground effect at low speeds can be quite rough. Fortunately, this condition exists for a predictable period, beginning as ground effect is encountered and terminating when ground contact is made or hovering is attained.

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Chapter 7

AUTOROTATION

If time does not permit a complete answer to the layman's question regarding the possibility of helicopter catastrophy in the event of engine failure, the simple statement that the rotor keeps on going "just like a windmill" is not a bad answer at all. Essentially, any propeller or rotor turning in the wind without shaft power is "windmilling". A toy propeller or a fan held into the wind will spin because it offers resistance to the wind. The greater the wind speed, the greater the RPM.

The condition of helicopter flight during which the main rotor is being driven by aerodynamic forces with no power from the engines is called *"autorotation"*. The required induced and profile power is supplied by aerodynamic forces resulting from an upward rotor inflow created by a gravity-induced glide path which can either be vertical or inclined.

Although we have mentioned "windmilling" and "autorotation" in literally the same breath, it should be stated that while both terms refer to the same basic phenomenon, windmilling implies a predominately *torque* producing action, while autorotation places the emphasis on *thrust*. Whether a windmilling rotor is essentially a torque producer or a thrust producer is determined by the pitch setting of the blades. Positive pitch settings on the moderately low side are best for autorotation while negative pitch settings are best for producing torque.

In Figure 87 notice that the blade has been set at a negative (below plane of rotation) pitch angle. The upward flow (inflow) of air into the rotor (the entire rotor is descending), combined with the rotational relative wind, creates a resultant relative wind and a new, resultant angle of attack.

A *lift component vector* drawn perpendicular to the resultant relative wind, together with a *drag component vector* drawn parallel to or as an extension of the resultant relative wind, creates a *resultant component vector* which is tilted considerably forward of a vertical reference. The addition of a gravity or weight factor then shows the existence of a strong torque force in the direction of rotation.

Figure 88 shows that a state of autorotative equilibrium can exist even though the blade has a positive pitch angle, so long as the lift-drag ratio is sufficiently high. The lift component vector, being tilted forward of vertical, and with the gravity or weight factor considered, produces a torque in the direction of rotation which balances a drag-induced torque or force

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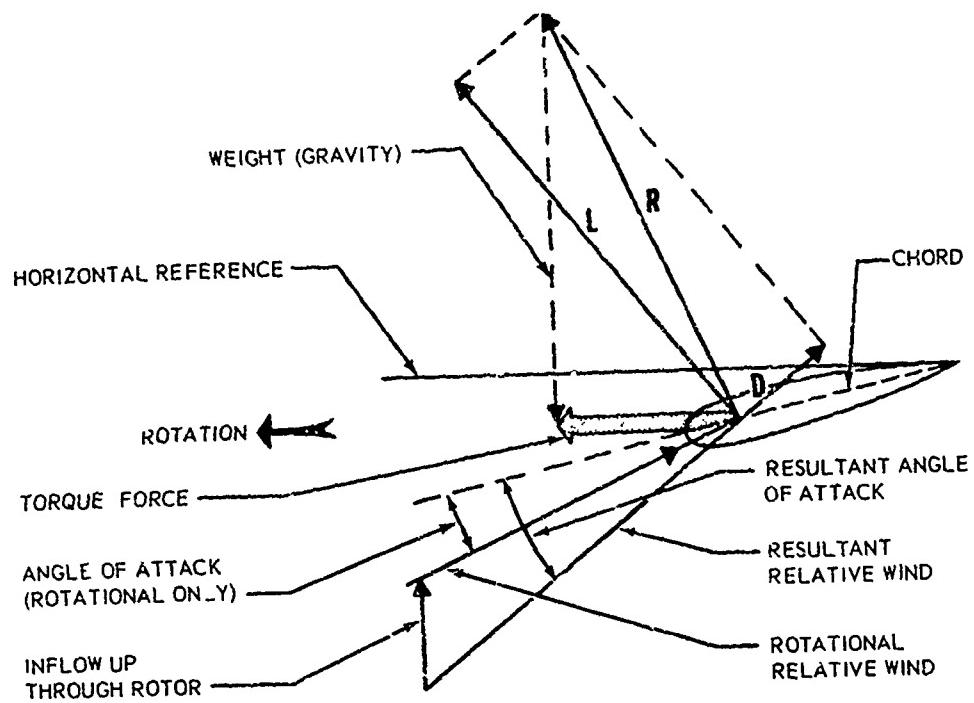
Figure 87 — Autorotation producing maximum torque.

which is opposite to rotation. Equilibrium is apparent because both forces are balanced and no in-plane forces exist which would tend to either speed up or slow down the rotor.

A study of Figure 87 would indicate that further decreasing the pitch angle (further increasing the *negative pitch angle*) would create more
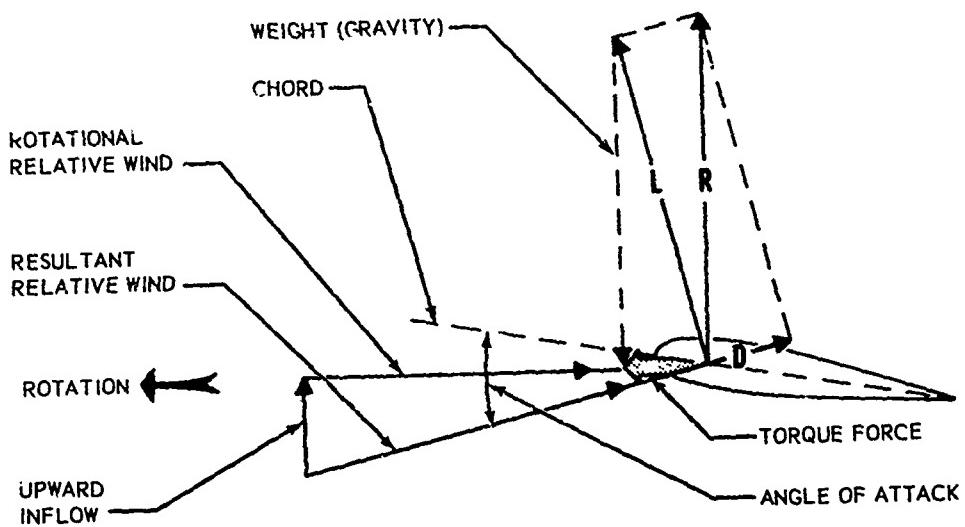
Figure 88 — Autorotation producing maximum thrust.

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torque and a greater acceleration of the rotor up to the point of maximum torque. Any increase of negative pitch angle beyond this point would slow the rotor and stop it when the blade chord reached vertical.

A study of Figure 88 indicates that as pitch is increased, drag would also increase thus slowing the rotor. If pitch were increased beyond the highest pitch still producing autorotation, the rotor would slow down below operational limits with catastrophic results.

It should be pointed out that Figures 87 and 88 represent only one blade element or section. Lift and drag vary radially. All sections of the blade must be considered in order to formulate total blade or rotor behavior. Working inboard sections of the blade or rotor generally experience accelerating forces, while outboard sections, due to the higher drag values induced by the higher rotational velocities, experience decelerating forces. The ideal autorotational pitch setting accounts for these variables in setting up autorotational equilibrium. It also accounts for the frictional drag forces caused by transmissions and shafting, as well as the power required by the tail rotor.
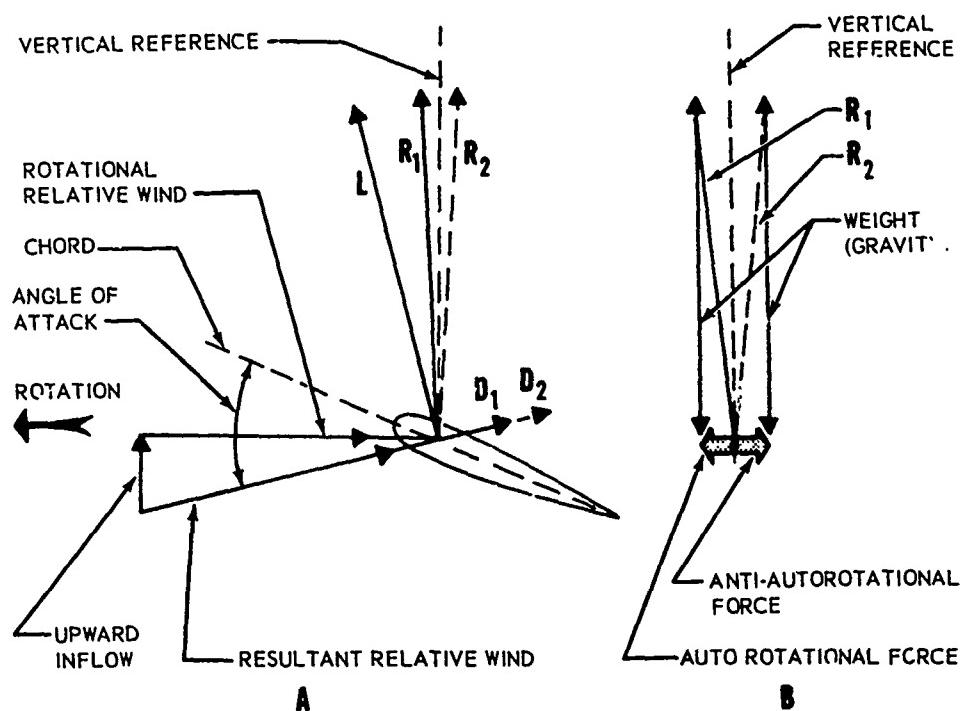

Figure 89 — Decelerating and accelerating forces.

Figure 89 (A) illustrates a rotor blade in autorotative equilibrium. The lift component vector is drawn perpendicular to the relative wind which is a resultant of the rotational and inflow velocities and directions. It lies for-

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ward of vertical. The solid-lined drag component vector D_1 and the solid lined lift-drag resultant R_1 illustrate the situation at about the inner two-thirds of the rotor. At the outer third of the rotor where the rotational velocity is substantially greater, there is more drag. This is shown by extending the drag component vector by the length of D_2. In recalculating the lift-drag resultant R_2 by considering the longer drag component vector D_2, we find that it has moved *aft* of vertical. Remembering that a weight or gravity factor suspended vertically from the top of each resultant would show the existence of a force in the direction in which the particular resultant is leaning, we can see in Figure 89 (B) that in any autorotating rotor system there is both an autorotative and a counter-autorotative force. Considering all factors, when all opposing forces balance, the rotor is in autorotational equilibrium.

CHORD

ANGLE OF ATTACK

RELATIVE WIND

ROTATION

L

R

D

B

SEE VIEW B

A
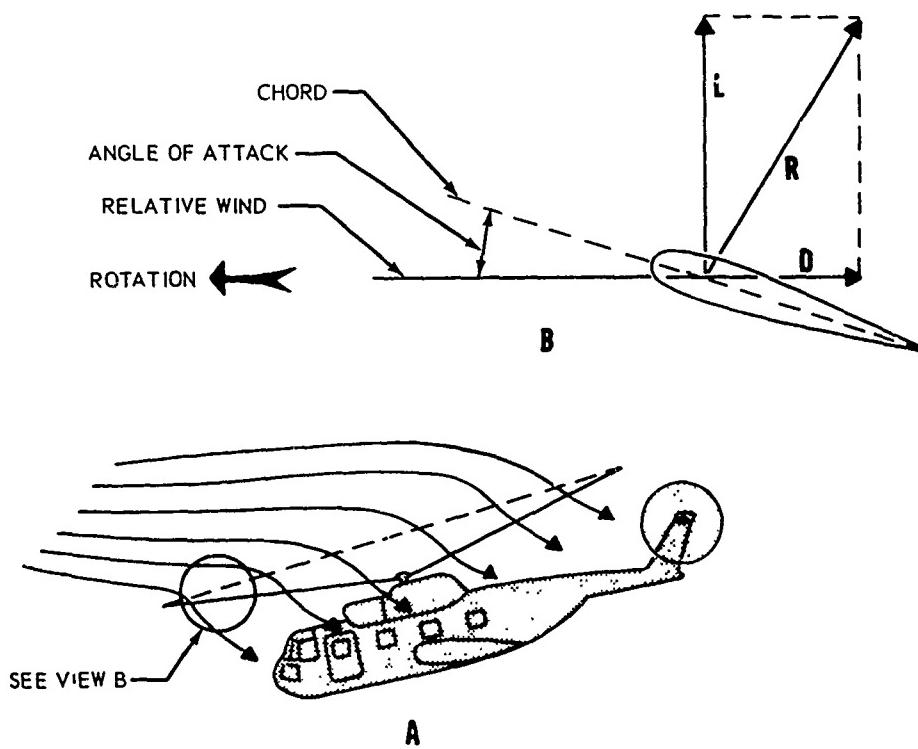
Figure 90 — Force vectors in high speed flight.

In Figure 90 (A) a helicopter in high speed forward flight is illustrated. The encountered air mass is being pulled down through the rotor in order to produce thrust. A blade element, Figure 90 (B), is shown above the helicopter. Notice that it is operating at a substantial angle of attack and that its lift-drag resultant is pointing upward and aft. This is a normal working state. So long as power is being applied to turn the rotor, there

is little concern about the location of the lift-drag resultant. When power is removed, however, whether intentionally or through actual loss, the position of the lift-drag resultant becomes of critical concern. If the relatively high pitch settings required for substantial forward speeds were maintained after a power failure, the lift-drag resultant would remain aft of vertical and decelerating forces would cause the rotor to slow down to a value below operating range with dire results. Obviously something must be done to move the lift-drag resultant to a position approximating that shown in Figure 88, i.e. near vertical.

In a properly rigged helicopter, this can easily be accomplished simply by dropping the collective pitch stick to its low pitch position and establishing a normal autorotative glide.
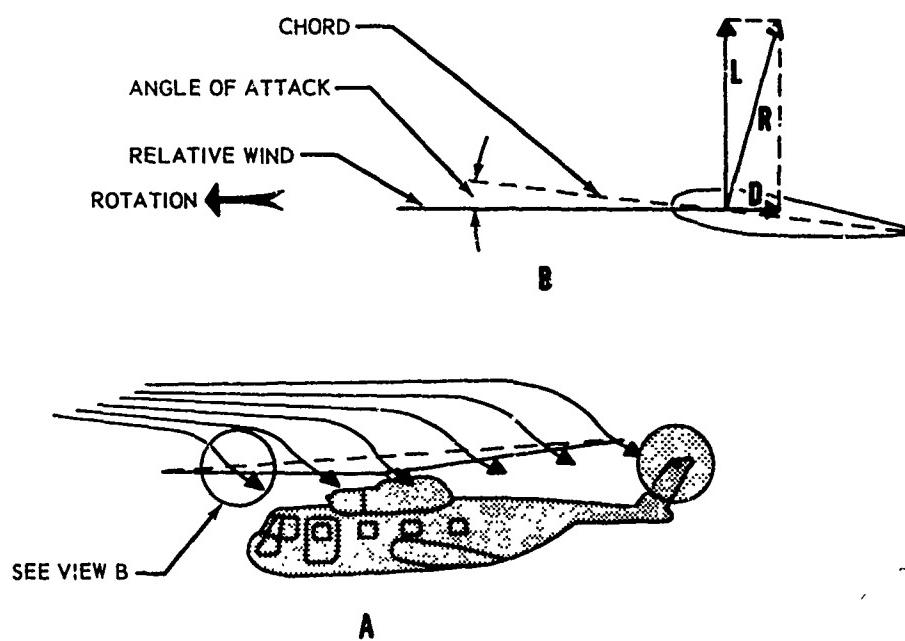

Figure 91 — Force vectors with loss of power and low collective.

In Figure 91 (B) the component vector diagram shows the situation following the loss of power and at the moment the pilot has dropped the collective pitch stick to the full low pitch position. Notice that from the power position as shown in Figure 90, to the power off position shown in Figure 91 (B), the lift component vector has been reduced in magnitude. More important, however, is the decreased amount of drag as evidenced by the shorter drag component vector in Figure 91 (B). Because both the lift component vector and the drag component vector have undergone changes, the lift-drag resultant has not only changed in magnitude, but in direction. *It has moved closer to vertical.*

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Needless to say, as power is removed and collective pitch lowered to the full low pitch position, the helicopter is going to descend. The pilot will establish a glide and maintain the proper airspeed which is generally between 50 to 75 knots, depending on the helicopter and its gross weight. Rotor RPM will stabilize very close to the autorotational RPM established for the helicopter when it was rigged and flight checked. Autorotational RPM will be found to be a few turns higher than the normal operating RPM.
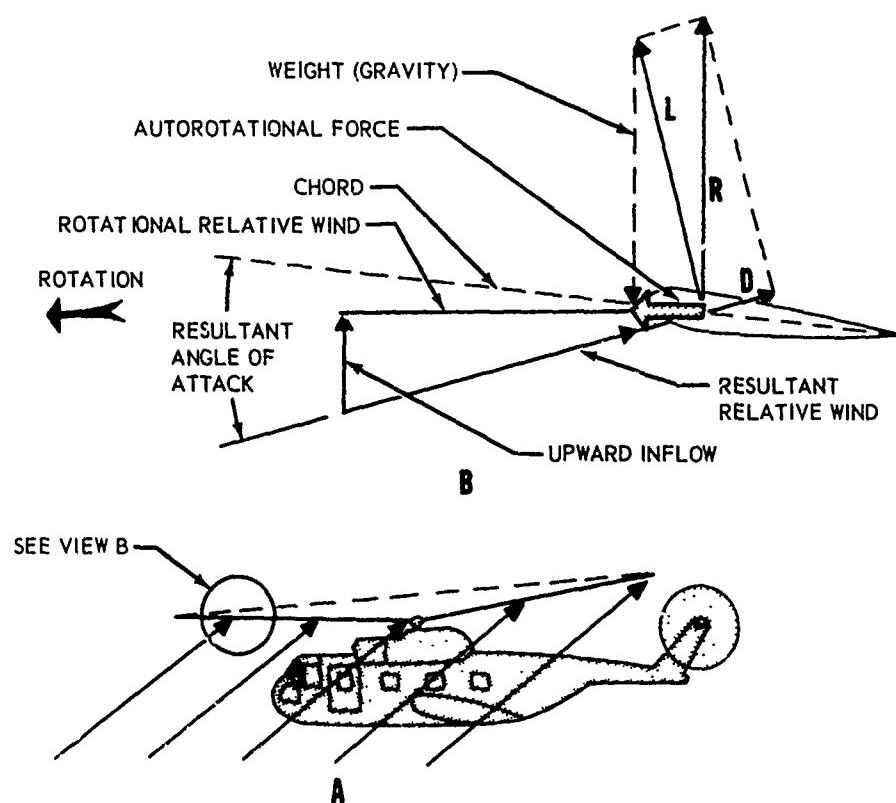

Figure 92 — Force vectors in autorotative descent.

In Figure 92 (A) the helicopter, with the recommended forward airspeed, is in its autorotational glide. The glide path relative wind is blowing up into the rotor. This up-flow (inflow), added to the rotational relative wind, changes the effective angle of attack to a greater value thus increasing the lift to a value greater than that experienced at the instant of dropping collective and prior to the start of the actual autorotational glide. In addition, the new angle of attack has tilted the lift component vector even further forward, thus increasing the autorotational force. This causes the increase in rotor RPM. These factors are shown in Figure 92 (B).

To sum up what has happened thus far, the pilot lowered collective pitch as soon as power was removed. This action reduced the lift but, more important, reduced the amount of drag. Reduction of the drag component vector changed the direction of the lift-drag resultant toward a more vertical position. As the helicopter settled into a glide path with adequate forward airspeed, the upcoming inflow through the rotor changed the value of the angle of attack and the direction of the relative wind. The higher angle of attack provided more lift for the descending helicopter while the direction of the new relative wind inclined the lift component vector further forward, thus creating the required autorotational force and an increase in rotor RPM.

The helicopter has now established an autorotational glide at the required forward airspeed, and rotor RPM has stabilized at the recommended value. A rate of descent commensurate with the model of helicopter being flown as well as certain flight condition variables has been established.

Once in the autorotational glide, and with the ground getting closer and closer, the pilot becomes extremely interested in two requirements for a successful landing. He wants to reduce his airspeed and he wants to reduce his rate of descent. He accomplishes both of these requirements by one control action. He pulls back on the *cyclic* pitch stick and thereby *"flares"* the rotor.

As illustrated in Figure 93, cyclically flaring the rotor accomplishes two things. First, as shown in Figure 93 (A), as the thrust of the rotor is tilted aft, a directional component of the thrust is directed aft. This effectively reduces the forward speed of the helicopter. With reference to the upflow (inflow) of air into the rotor, it is seen that flaring the rotor effectively increases the angle of attack of all blades, regardless of their cyclic pitch. This increase in angle of attack, as shown in Figure 93 (B), naturally causes an increase in the magnitude of the lift component vector. The additional lift effectively reduces the rate of descent of the helicopter. Because the lift component vector has lengthened, the autorotational force increases in magnitude and an increase in rotor RPM will be noticed.

Having reduced his rate of descent to a satisfactory value, the pilot then applies forward cyclic stick to bring the helicopter to a more or less level attitude once again. With the recommended forward speed for a roll-on landing established, generally 35 to 45 knots but depending on the helicopter and flight conditions, he then uses collective pitch to cushion the roll-on landing, trading his rotor energy for additional lift.

WEIGHT (GRAVITY)

AUTOROTATIONAL FORCE

ROTATIONAL RELATIVE WIND

INFLOW

RESULTANT
ANGLE OF ATTACK

ROTATION

L

R

CHORD

D

RESULTANT
RELATIVE WIND

B

SEE VIEW B

A
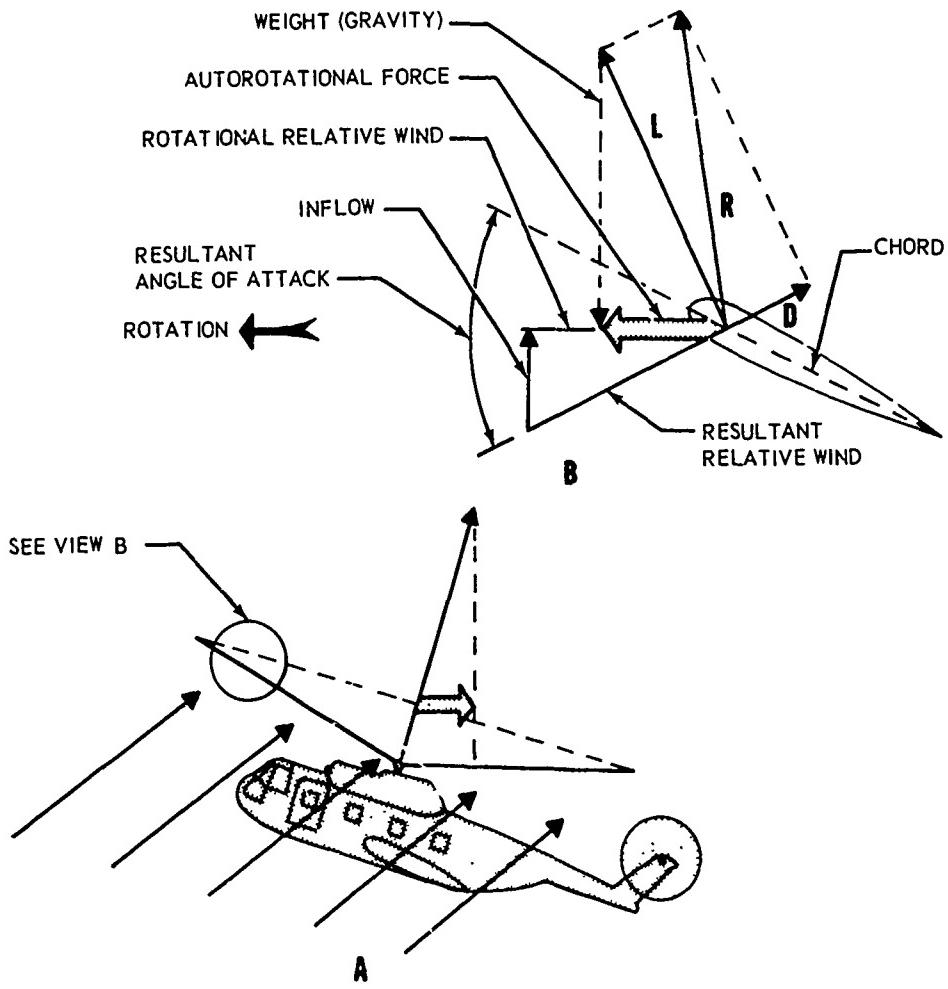
Figure 93 — Force vectors in autorotative flare.

While autorotation should only be performed in accordance with in-
structions in the flight handbook, and these instructions *always* recom-
mend forward speed, vertical autorotation is just as aerodynamically sound
as autorotation with forward airspeed. The big difference is that the rate
of descent is vastly greater.